Department of
ENERGY TECHNOLOGY

E.T.

AC MicroGrids

Industrial PhD course on Microgrids in Theory and Practice

April 24 – 25, 2017

AALBORG UNIVERSITET

Lecturers

Josep M. Guerrero, Professor, Aalborg University, Denmark
Juan C. Vasquez, Associate Professor, Aalborg University, Denmark
Ernane A. Coelho, Associate Professor, Univ. Federal de Uberlândia, Brazil
Qobad Shafiee, Assistant Professor, University of Kurdistan, Iran
Yajuan Guan, Postdoc, Aalborg University, Denmark

www.microgrids.et.aau.dk

Josep M. Guerrero received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics, in 1997, 2000, and 2003, from the Technical University of Catalonia, Barcelona, Spain. He is an Associate Professor at the same university, where he teaches courses on digital signal processing, control theory, and renewable energy systems. Since 2011, he has been a Full Professor on MicroGrids at the Department of Energy Technology, Aalborg University. His research interests include distributed and hierarchical control of AC and DC MicroGrids.
Dr. Guerrero is an Associate Editor of the IEEE Transactions on Industrial Electronics, the IEEE TRANSACTIONS ON POWER ELECTRONICS, and the IEEE Industrial Electronics Magazine. He is the Guest Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS for the Special Issue: “Power Electronics for Microgrids”. Currently, he chairs the IEEE Industrial Electronics Society Technical Committee on Renewable Energy Systems.

Juan C. Vasquez received the B.S. degree in Electronics Engineering from Autonoma University of Manizales, Colombia in 2004 where he has been teaching courses on digital circuits, servo systems and flexible manufacturing systems. He received the PhD degree from the Technical University of Catalonia, Barcelona, Spain in 2009, where he taught courses on renewable energy systems. Currently he is working as Assistant Professor at Aalborg University, Department of Energy Technology. His research interests include modelling, simulation, and power management applied to Distributed Generation in Microgrids.

Ernane Antônio Alves Coelho received the B.S. degree in Electrical Engineering from the Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, Brazil, the M.S. degree from the Universidade Federal de Santa Catarina, Florianópolis, Brazil, and the Ph.D. degree from UFMG in 1987, 1989, and 2000, respectively. He is currently associate professor at the Universidade Federal de Uberlândia, state of Minas Gerais, Brazil. His research interests are PWM inverters, Power-factor Correction, Microgrid Modelling and Control, Digital Controllers using microcontrollers and DSP's.

Qobad shafiee received the B.S. degree in electronics engineering from Razi University, Kermanshah, Iran, in 2004, the M.S. degree in electrical engineering-control from Iran University of Science and Technology, Tehran, Iran, in 2007, and the Ph.D. degree in electrical engineering-microgrids from the Department of Energy Technology, Aalborg University, Aalborg, Denmark, in 2014. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, Iran, where he was a Lecturer, from 2007 to 2011. He is Vice Program Leader of the Smart/Micro Grids Research Center at University of Kurdistan. He was a Visiting Scholar with the Electrical Engineering Department, University of Texas-Arlington, Arlington, TX, USA, in 2014. He was a Post-Doctoral Fellow with the Department of Energy Technology, Aalborg University, in 2015. His main research interests include modeling, energy management, control of microgrids, and modeling and control of power electronics converters. He has been a Guest Associate Editor of the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS Special Issue on structured dc microgrids. He is a member of PELS, IAS, and PES Societies.

Yajuan Guan received the B.S. degree and M.S. degree in electrical engineering from the Yanshan University, China, and the Ph.D. degree in power electronics from the Aalborg University, Denmark, in 2007, 2010 and 2016 respectively. From 2010 to 2012, she was an Assistant Professor in Institute of Electrical Engineering (IEE), Chinese Academy of Sciences (CAS). Since 2013, she has been a Lecturer in IEE; CAS. She is currently a Postdoctoral Fellow with Aalborg University. Her research interests include microgrids, distributed generation systems, and power converter for renewable energy generation systems.

Fee

6000 DKK for PhD students/Academics outside of Denmark and 1500 DKK for PhD students in Denmark, who is not from AAU. 8000 DKK for the Industry.

AC Microgrids

Industrial/PhD course on
AC Microgrids
in Theory and Practice

Industrial/Ph.D. Course in
AC Microgrids
– in theory and practice

April 24 – 25
2017

Department of Energy Technology
Aalborg, Denmark

Background of the course

Worldwide electrical grids are expecting to become smarter in the next future. In this sense, the increasing interest in intelligent and flexible microgrids able to operate in island or connected to the grid, which will be a keypoint to cope with new functionalities, as well as integration of renewable energy resources.

A microgrid can be defined as a part of the grid with elements of prime energy movers, power electronics converters, distributed energy storage systems and local loads, that can operate autonomously but also interacting with main grid. The functionalities expected for these small grids are: black start operation, frequency and voltage stability, active and reactive power flow control, active power filter capabilities, and storage energy management. This way, the energy can be generated and stored near the consumption points, increasing the reliability and reducing the losses produced by the large power lines.

The course starts giving some examples of microgrid in the world. The course is mainly focused on three-phase voltage source inverters. The modeling and control of these power electronics converters is presented. Concepts like frequency and voltage droop control are explained in detail, as well as the virtual impedance concept.

This course also introduces the study of the hierarchical control of AC Microgrids. Secondary control issues are introduced to regulate frequency and amplitude voltage of the microgrid. Finally, tertiary control issues, synchronization and grid interactivity between the grid and the microgrid are analyzed. Finally, voltage unbalance and harmonic compensation by using decentralized controllers is also presented.

No less than 50% of the course time will be spent on the case exercises.

Keep yourselves updated www.microgrids.et.aau.dk

Course Program

Day 1, 08.30-16.30

L1	Microgrids Systems Overview
L2	Control, Modeling, and Implementation of Microgrids
Lab I	Design of Inner Control Loops for VSI
Lab II	Evaluation of a Stand-alone VSI with Voltage Control
Lab III	Design and Small Signal Analysis of Droop Controller and Virtual Impedance

Day 2, 08.30-16.00

L3	Distributed Energy Storage Systems
L4	Hierarchical Control of AC Microgrids
L5	Control Strategies for AC Microgrids
Lab IV	Evaluation of Grid-Interactive VSI with Droop control
Lab V	Coordinated Primary Control of an Islanded Microgrid
Lab VI	Centralized and Distributed Secondary Control of an Islanded Microgrid

Lecturers

Josep M. Guerrero, Professor, Aalborg Univeristy, Denmark, joz@et.aau.dk

Juan C. Vasquez, Assistant Professor, Aalborg University, Denmark, juq@et.aau.dk

Ernane Antônio Alves Coelho, Associate Professor, Universidade Federal de Uberlândia, Brazil, ernane@ufu.br

Qobad shafiee, Assistant Professor, University of Kurdistan, Sanandaj, Iran, q.shafiee@uok.ac.ir

Yajuan Guan, Postdoc, Aalborg Univeristy, Denmark, ygu@et.aau.dk

Course Location

Aalborg University,
Department of Energy Technology
Pontoppidanstraede 101, Room 19
DK-9220 Aalborg East, Denmark

Accommodation and transport

For hotel, transport information and booking please check: www.et.aau.dk/phd/phd-courses

Credits 2.0 ECTS

Prerequisites

In order to be able to perform the exercises, the course participants should bring their notebooks with Matlab pre-installed (in case that it is not possible, some computers will be available).

Further information

Malena Østergaard Beck
Office Administrator
Department of Energy Technology
Phone +45 99403320
Email: mbe@et.aau.dk

Registration

Please fill out the registration form available at:
http://phdcourse.aau.dk/index.php?list=29586

Registration closed on **April 3rd, 2017**.

List of participants for Industrial/Ph.D. Course in AC Microgrids

8th Edition: April 24 – April 25, 2017

Course Participants

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PHD Course on AC - MICROGRIDS

	DAY1: INTRODUCTION AND BASIC CONTROL	DAY2: AC MICROGRIDS
08:30	LECTURE – P101-19	LECTURE – P101-19
	Registration Course Overview Presentation of Speakers	L3 - Distributed Energy Storage Systems
	L1 - Microgrids Systems Overview	L4 - Hierarchical Control of AC Microgrids
10:00	COFFEE BREAK	
10:30	LECTURE – P101-19	LECTURE – P101-19
	L2 - Control, Modeling, and Implementation of Microgrids	L5 – Control Strategies for AC Microgrids
12:00	LUNCH BREAK	
13:00	LABORATORY – P109-19	LABORATORY – P109-19
	Lab I - Design of Inner Control Loops for VSI	Lab IV - Evaluation of Grid-Interactive VSI with Droop
	Lab II - Evaluation of a Stand-alone VSI with Voltage Control	Lab V -Coordinated Primary Control of an Islanded Microgrid
14:30	COFFEE BREAK	
15:00	LABORATORY – P109-19	LABORATORY – P109-19
	Lab III - Design and Small Signal Analysis of Droop Controller and Virtual Impedance	Lab VI - Centralized and Distributed Secondary Control of an Islanded Microgrid
16:00		Evaluation and Closing Session

Presentation of Speakers

Josep M. Guerrero, Prof. Aalborg University

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Who is Josep M. Guerrero

He received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, in 1997, 2000 and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. From 2012 he has been a guest Professor at the Chinese Academy of Science and the Nanjing University of Aeronautics and Astronautics; and from 2014 he has been chair Professor in Shandong University.

Dr. Guerrero is an Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and the IEEE Industrial Electronics Magazine, and an Editor for the IEEE TRANSACTIONS on SMART GRID. He has been Guest Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS Special Issues: Power Electronics for Wind Energy Conversion and Power Electronics for Microgrids; the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Special Sections: Uninterruptible Power Supplies systems, Renewable Energy Systems, Distributed Generation and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter; and the IEEE TRANSACTIONS on SMART GRID Special Issue on Smart DC Distribution Systems. He was the chair of the Renewable Energy Systems Technical Committee of the IEEE Industrial Electronics Society. In 2014 he was awarded by Thomson Reuters as Highly Cited Researcher, and in the same year he was elevated as IEEE Fellow for his contributions on "distributed power systems and microgrids.

Who is Juan C. Vasquez

He has received B.S degree and M.S in Electronics Engineering from the Universidad Autonoma de Manizales (UAM), Colombia with specialization in control and industrial automation, where he has been teaching courses on digital circuits, servo systems, and systems of flexible manufacturing.

Since 2008, he is involved with the Power Electronic and Control Systems (SEPIC) Research Team, Department of Electrical and Electronic Engineering, Technical University of Catalonia, Barcelona, where he got a Ph.D grant by the Spanish Ministry of Education and Science.

In December 2010 he got the Ph.D. degree in Automatic Control, Robotics, and Artificial Vision where he was teaching courses on Renewable Energy Systems. Recently, He is working at Aalborg University as an Assistant Professor in Microgrids.

His research interests include system modeling, simulation, hierarchical control and power management applied to Distributed power Generation systems in AC/DC Microgrids. He is currently member of the Technical Committee on Renewable Energy Systems TC-RES.

Who is Ernane Antônio Alves Coelho

Ernane Antônio Alves Coelho received the B.S. degree in Electrical Engineering from the Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, Brazil, the M.S. degree from the Universidade Federal de Santa Catarina, Florianópolis, Brazil, and the Ph.D. degree from UFMG in 1987, 1989, and 2000, respectively.

He is currently associate professor at the Universidade Federal de Uberlândia, state of Minas Gerais, Brazil. His research interests are PWM inverters, Power-factor Correction, Microgrid Modelling and Control, Digital Controllers using microcontrollers and DSP's.

Who is Qobad Shafiee

Qobad Shafiee (S'13–M'15–SM'17) received the B.S. degree in electronics engineering from Razi University, Kermanshah, Iran, in 2004, the M.S. degree in electrical engineering-control from Iran University of Science and Technology, Tehran, Iran, in 2007, and the Ph.D. degree in electrical engineering-microgrids from the Department of Energy Technology, Aalborg University, Aalborg, Denmark, in 2014. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, Iran, where he was a Lecturer, from 2007 to 2011. He is Vice Program Leader of the Smart/Micro Grids Research Center at University of Kurdistan. He was a Visiting Scholar with the Electrical Engineering Department, University of Texas-Arlington, Arlington, TX, USA, in 2014. He was a Post-Doctoral Fellow with the Department of Energy Technology, Aalborg University, in 2015.

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Who is Yajuan Guan

Yajuan Guan (S'14) received the B.S. degree and M.S. degree in Electrical Engineering from the Yanshan University, Qinhuangdao, Hebei, China, in 2007 and 2010 respectively. From 2010 to 2012, she was an Assistant Professor in Institute of Electrical Engineering (IEE), Chinese Academy of Sciences (CAS). Since 2013, she has been a Lecturer in IEE; CAS. She is currently working toward her Ph.D. degree at the Department of Energy Technology, Aalborg University, Denmark,

Her research interests include microgrids, distributed generation systems, power converter for renewable energy generation systems, and ancillary services for microgrids.

Who is Mingshen Li

Mingshen Li(S'15) received the B.S. degree in electrical engineering from Chongqing University, Chong-qing, China in 2013, and the M.S. degree from Hunan University, Changsha, China, in 2016. He is currently working toward his Ph.D. degree in Aalborg University, Aalborg, Denmark.

His research interests include coordinative operation and optimal control for multiple microgrids cluster systems, power quality control of distributed generation.

Course Schedule

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Microgrids Overview

Josep M. Guerrero, Prof. Aalborg University

AC Microgrids

Industrial/PhD course on Microgrids
in Theory and Practice

Microgrids Overview

Josep M. Guerrero, Prof.
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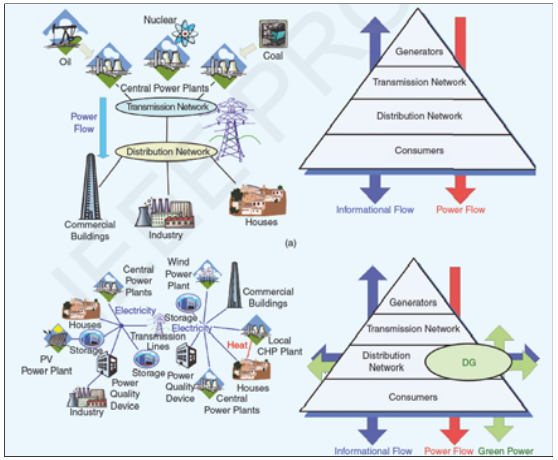
Outline

- Distributed power systems
- Microgrid definition
- Microgrid configurations
- Examples of Microgrid Projects
- Uninterruptible Power Systems (UPS)

Centralized vs Distributed Power Systems

General advantages of the DPS:

- Redundancy
- Modularity
- Fault tolerance
- Efficiency
- Reliability
- Easy maintenance
- Smaller size
- Lower design cost

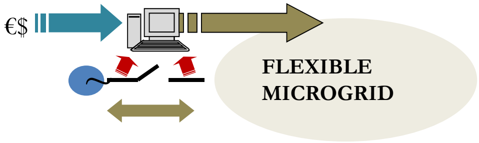


Distributed Power Systems

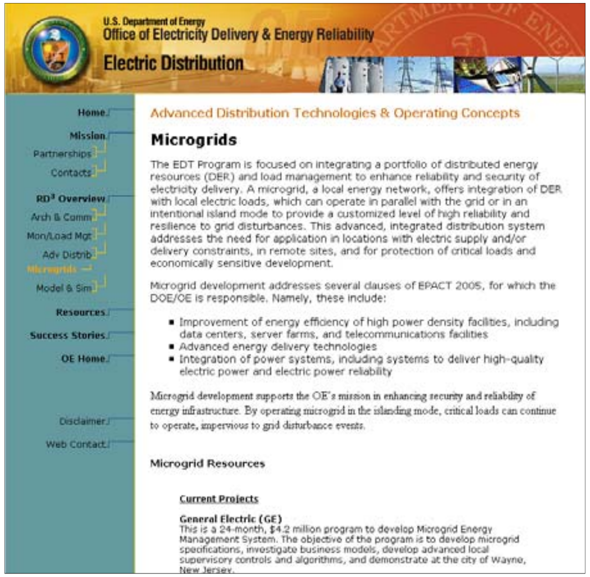
- Nowadays problem: energy crisis & climatic change
- Kyoto's protocol: reduction of CO2 emission
- Penetration of renewable energy:
  - Photovoltaic
  - Wind
  - Hydrogen
  - Micro-turbines
- Small energy storage systems:
  - Flywheels
  - Super-capacitors
  - Compressed air devices
  - Mini-hydraulics
- Energy production decentralization:
- Distributed generation and **Microgrids**

What is a Microgrid?

- Coordinated electrical subsystem with
  - Multiple Distributed Energy Resources (DER)
  - Multiple loads
  - Distribution voltage interconnections
  - Capable of (macro) grid independent and dispatchable grid interactive operation
- What's driving it?
  - Deregulation driving system operation close to capacity limits
  - Transmission constraints driving generation sources closer to loads
  - Demand for improved power availability and power quality
  - Industry interest in DER potential for clean/efficient energy (electrical and thermal)
- **Requires a systemic approach not merely an interconnection of DER components**



Microgrid Definition by US-DOE



Advanced Distribution Technologies & Operating Concepts

Microgrids

The EDT Program is focused on integrating a portfolio of distributed energy resources (DER) and load management to enhance reliability and security of electricity delivery. A microgrid, a local energy network, offers integration of DER with local electric loads, which can operate in parallel with the grid or in an intentional island mode to provide a customized level of high reliability and resilience to grid disturbances. This advanced, integrated distribution system addresses the need for application in locations with electric supply and/or delivery constraints, in remote sites, and for protection of critical loads and economically sensitive development.

Microgrid development addresses several clauses of EPACT 2005, for which the DOE/OE is responsible. Namely, these include:

- Improvement of energy efficiency of high power density facilities, including data centers, server farms, and telecommunications facilities
- Advanced energy delivery technologies
- Integration of power systems, including systems to deliver high-quality electric power and electric power reliability

Microgrid development supports the OE's mission in enhancing security and reliability of energy infrastructure. By operating microgrid in the islanding mode, critical loads can continue to operate, impervious to grid disturbance events.

Microgrid Resources

Current Projects

General Electric (GE)
This is a 24-month, $4.2 million program to develop Microgrid Energy Management System. The objective of the program is to develop microgrid specifications, investigate business models, develop advanced local supervisory controls and algorithms, and demonstrate at the city of Wayne, New Jersey.

Outline

- Distributed power systems
- Microgrid Definition
- Microgrid Configurations
- Ex of Microgrids
- UPS
- Storage technology

Microgrid Particularities

1. Single Facility (<2MW)
   - Smaller individual facilities with multiple loads, e.g. hospitals, schools
2. Multi-Facility (2-5MW)
   - Small to larger traditional CHP facilities plus a few neighboring loads exclusively C&I
3. Feeder (5-20MW)
   - Small to larger traditional CHP facilities plus many or large neighboring loads, typically C&I
4. Substation (>20MW)
   - Traditional CHP plus many neighboring loads. Will include C&I plus residential
5. Rural Electrification
   - Rural villages of many emerging markets of India, China, Brazil etc., as well as rural settlements found in Europe and North America

Microgrid Particularities

Challenges: Isolated power systems are not new, but…

- Distribution protection and control practice is largely incompatible with Microgrid concept
    - *Bi-directional power flows*
    - *Unit level voltage and VAR support*
- Non-conventional generation will require new unit control and protection
- Strategies for successful Microgrid operation
    - *Variability of renewables*
    - *Low overload, short circuit ratings*
    - *Power rate limits*
    - *Potential for active load control (e.g., water and hydrogen production)*
- Supervisory controls will be needed to achieve the full operating potential
- Total energy optimization (electrical and thermal)
    - *Load management*
    - *Unit commitment*
    - *Aggregation and system performance*
    - *Data acquisition*
- Business, regulatory, and tariff structures are presently incompatible with multiparty MGs

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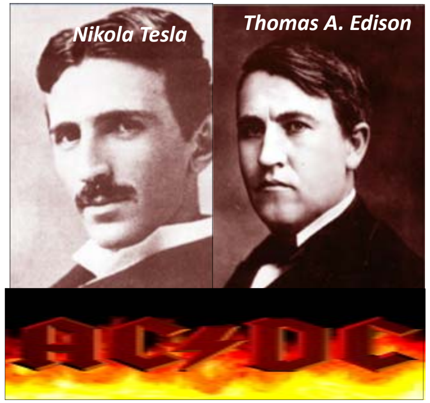
Microgrid Particularities

AC vs DC Microgrids

- Thomas A. Edison: “My personal desire would be to prohibit entirely the use of alternating currents. They are as unnecessary as they are dangerous. I can therefore see no justification for the introduction of a system which has no element of permanency and every element of danger to life and property.”



Microgrid Configurations

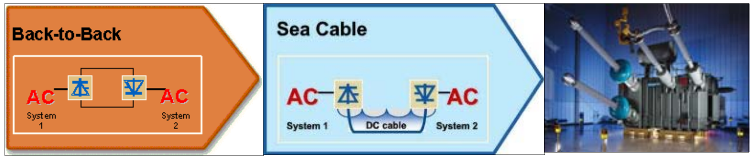
Advantage of **DC transmission** systems

- No reactive power loading of the transmission line
- Complete control of energy flow

No reactive power loading of the transmission line

- Reduced losses
- Why Back to Back links?
- Different system frequencies
- No additional short circuit power contribution to connected networks

Fully controllable power flow



Microgrid Configurations

Problems in AC Microgrids:

- Synchronization of distributed generators
- Inrush current (transformers, Induction motors, Induction generators)
- Three-Phase Unbalance (single-phase loads, single-phase generators such as photovoltaic)

Recent Trends:

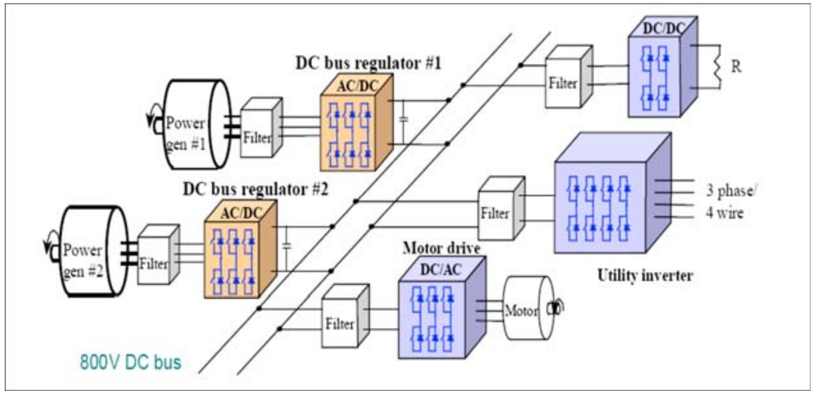
- Introduction of many Inverter loads (AC/DC and DC/AC conversions are included)
- Introduction of distributed generations with DC output (photovoltaic, fuel cell, variable speed type wind turbine, microturbine, gas engine)
- Needs for higher quality power
- DC-coupled Microgrids
- DC Microgrids/nanogrids
- DC distributed power systems (DPS)
- Applications: VRM, -48 V telecom systems, DC-link for UPS systems
- Isolated systems: avionic, automotive, marine…

Microgrid Configurations

Distributed power systems in DC

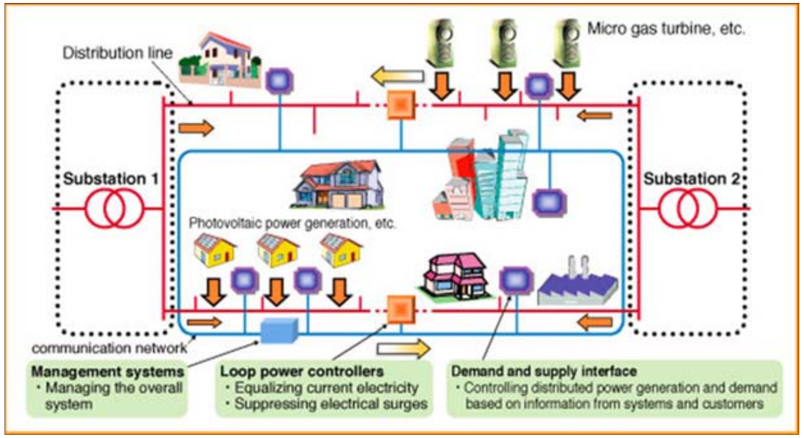
AC/DC converters connected in parallel

Loads, DC/DC, DC/AC, speed drives



Microgrid Configurations

Demand and Supply



Management systems
- Managing the overall system

Loop power controllers
- Equalizing current electricity
- Suppressing electrical surges

Demand and supply interface
- Controlling distributed power generation and demand based on information from systems and customers

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Microgrid Configurations

PhotoVoltaic (PV) Systems -The nature of the DG

- DC Microgrids

PV systems

Grid connected	**Islanded**
✓ Current source	Voltage Source
✓ MPPT	Batteries
✓ Anti-islanding operation	Cannot run connected to the grid
✓ PLL	Voltage and Frequency Control

Nowadays opposite philosophies, in near future...

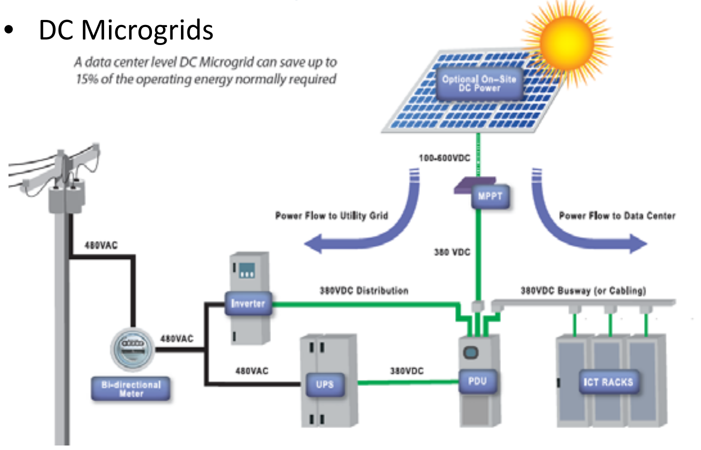
...we need something in the middle, flexible and robust

Microgrid Configurations

PhotoVoltaic (PV) Systems -The nature of the DG

- DC Microgrids

A data center level DC Microgrid can save up to 15% of the operating energy normally required



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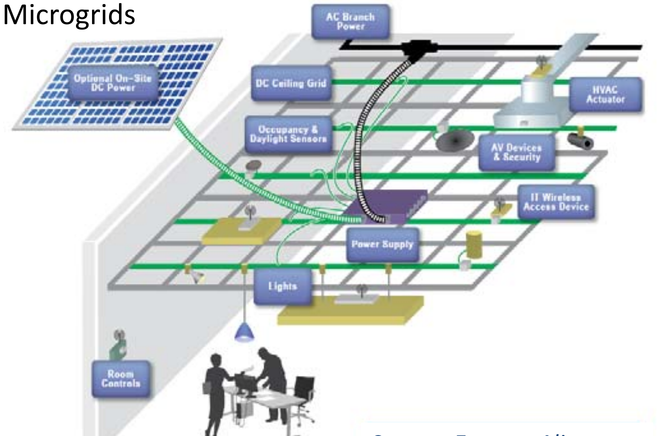
Microgrid Configurations

PhotoVoltaic (PV) Systems -The nature of the DG

- DC Microgrids



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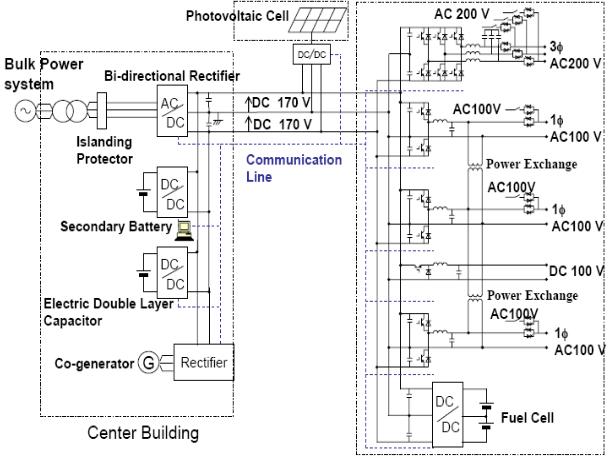
Microgrid Configurations

DC Microgrids

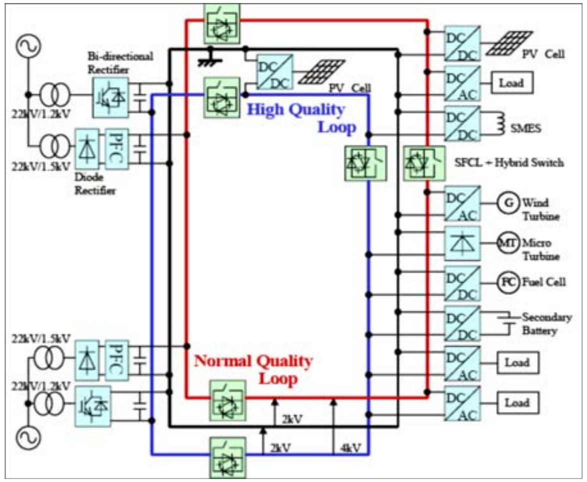
- *Bidirectional AC/DC*
- *Energy storage DC/DC interfaces, batteries, supercapacitors*



Microgrid Configurations

DC Microgrid

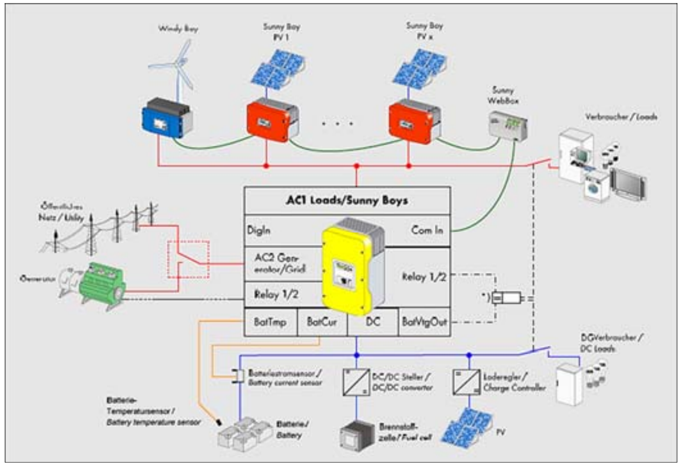
- *Different levers of power and reliable quality*



Microgrid Configurations

AC-DC Hybrid Microgrid

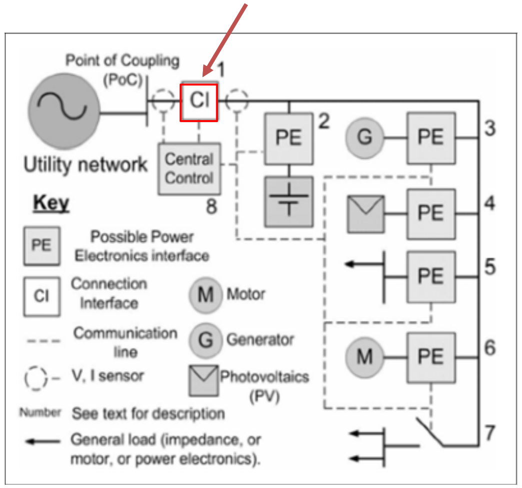
Hierarchy of loads



Source: SMA

Microgrid Configurations

Connection interface (CI)



Microgrid Configurations

Standarized Communications for Next Power Grid

- **IEC 61850 Standard**

  Communications in substations. Methods:

1) **Functional decomposition**. Understand relation bewer components, presented in terms of logical nodes (LN) to describe functions, subfunctions and functional interfaces.
2) **Data flow**. Understand communication interfaces between the distributed functional components and the performance requeriments.
3) **Information modeling**. Define the abstract semantics and sintax of the information exchanged, and it is presented in terms of data object classes and types, attributes, abstract object methods (services), and their relationships .

Timbus et Al. Management of DER Using Standarized Communications and modern Technologies

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Microgrid Configurations

Standard Extentions for Distributed Generation

- IEC 61850 Extensions:

  Communications data model for DGs like PV, CHP, hydro…

  - *IEC 61850-7-410 Hydro*
  - *IEC 61850-7-420 Distributed Energy Resources*

- IEC 61400-25 Extension: Wind Turbines

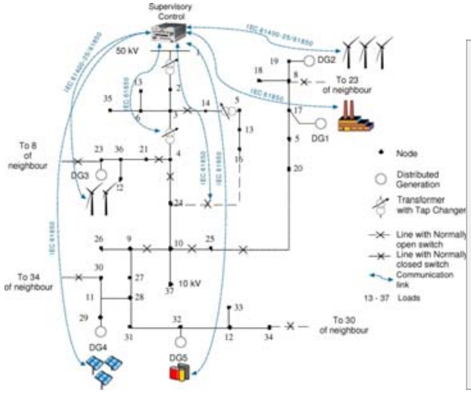
Timbus et Al. *Management of DER Using Standarized Communications and modern Technologies*

Microgrid Configurations

Communications data model

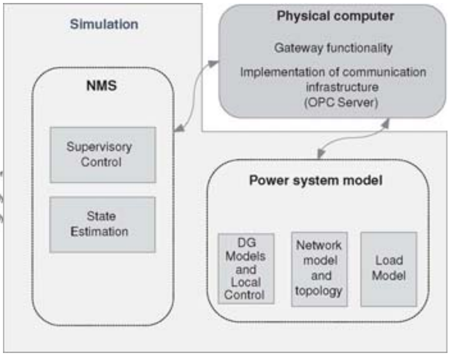
IEEE 37-bus model

Active distribution grid with DGs



Simulation set-up

The gateway computer contains: communication model provided by IEC 61850 & IEC 61400-25 to describe the physical devices in the network model.



Timbus et Al. *Management of DER Using Standarized Communications and modern Technologies*

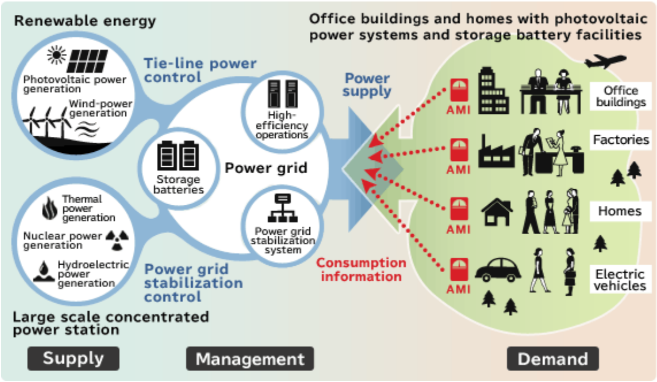
Outline

- Distributed power systems
- Microgrid Definition
- Microgrid Configurations
- Ex of Microgrids
- UPS

Microgrid examples

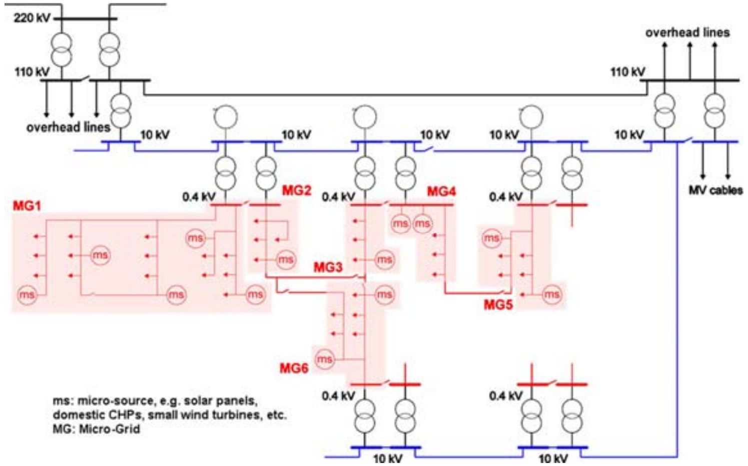
Energy demand and supply

Hitachi's Smart Grid Concept



Microgrid examples

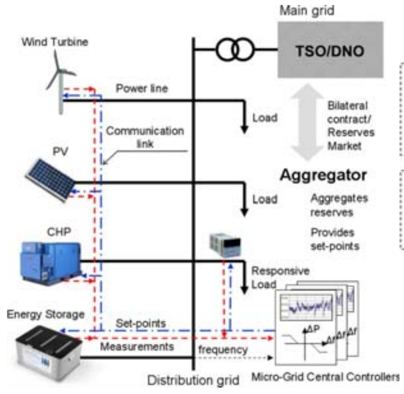
Distribution network with multiple MG setup



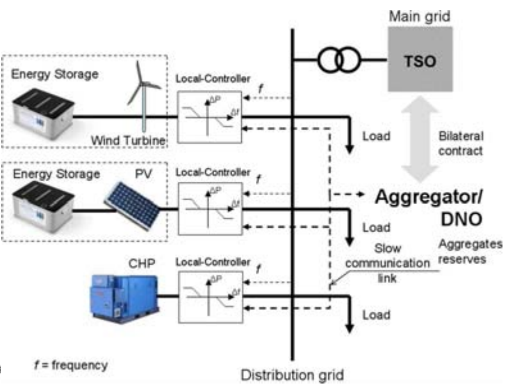
Microgrid examples

Distribution network with multiple MG setup

Centralized Control

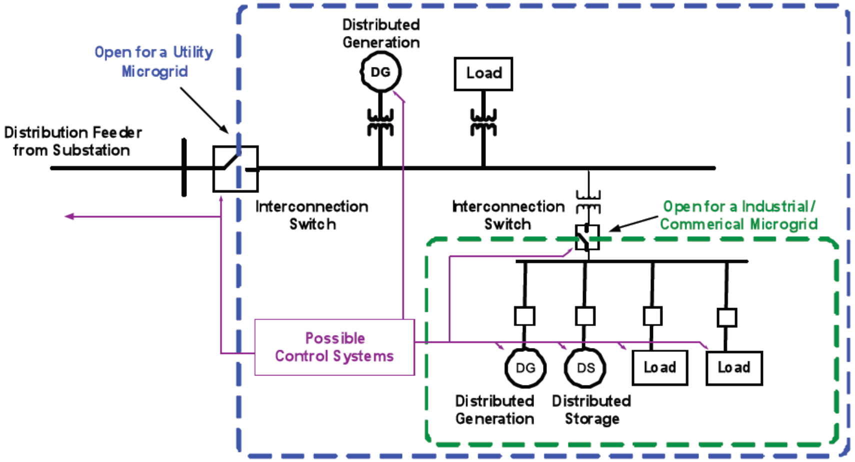


Decentralized control



Microgrid examples

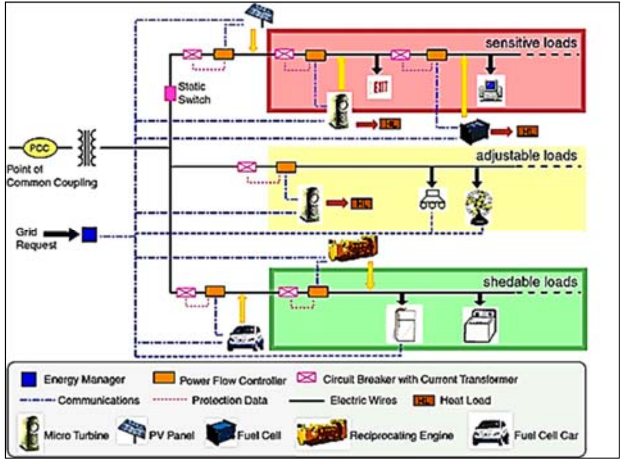
IEEE 1547.4 for DR Islanded Systems



Microgrid examples

Microgrid proposed by the *CERTS* (Consortium for Electric Reliability Technology Solutions)

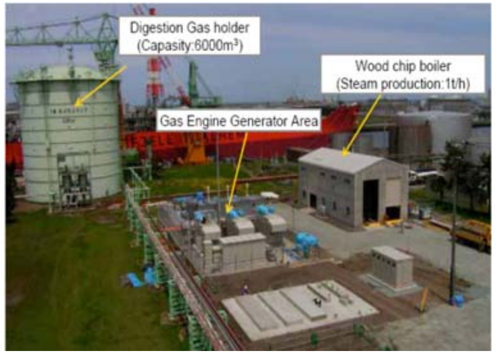
MG technologies for fitting different types of load

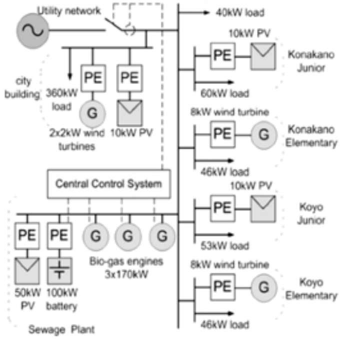


Microgrid examples

Hachinohe Project (Japan)

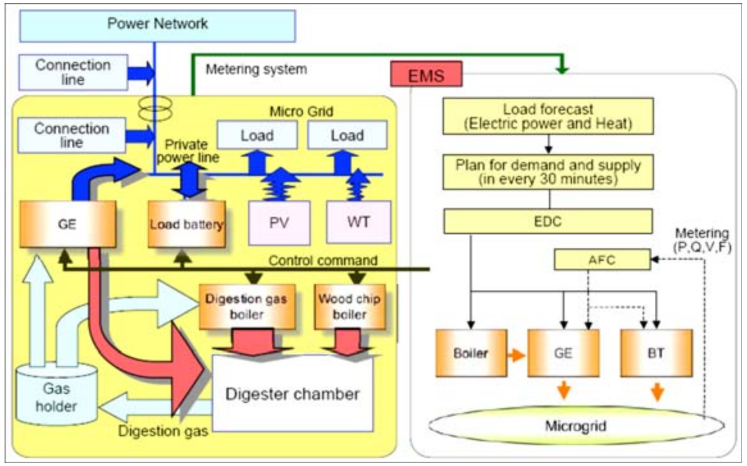
- Tecnnology demo
- GT+Biomass+PV+WT+BAT
- Load – 610 kW (Sewage Plant+Schools)





Microgrid examples

Hachinohe Project (Japan)



Microgrid examples

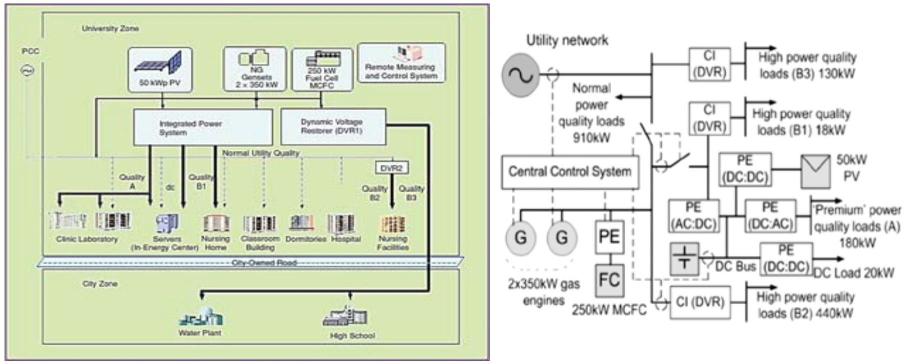
Sendai Project – Japan

- 1 MW Microgrid with sensitive loads!

Microgrid examples

Sendai Project – Japan

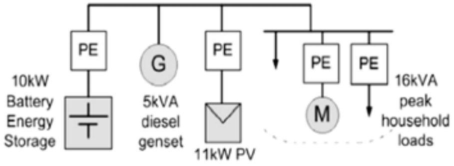
- 1 MW Microgrid with sensitive loads!

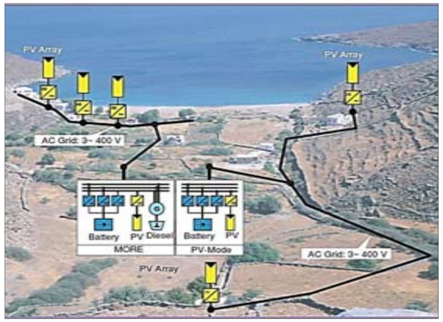


Microgrid examples

Kynthos Island- Greece (SMA)

✓*Remote location*
✓*PV resource + storage*

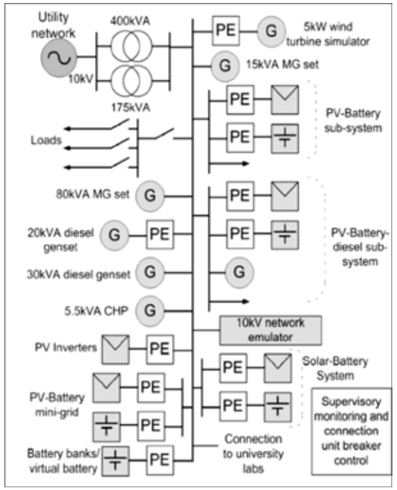




Microgrid examples

ISET-Demotec, Kassel, Germany

Technology demonstration

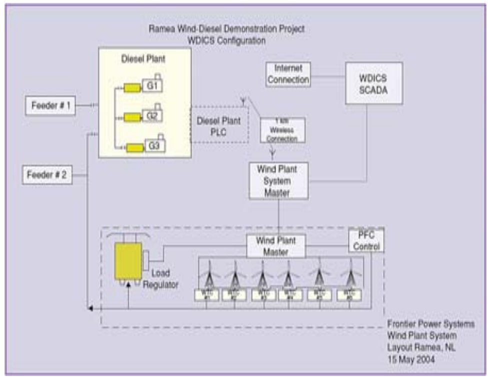


Microgrid examples

Ramea integrated wind-diesel project

(Newfoundland and Labrador Canada)

- *Six 65 kW Windmatic wind turbines*
- *Technology demonstration project*
- *WDICS (Wind-Diesel Integrated Control System)*
- *System Master*
- *Wind Plant Master*
- *Load Regulator*
- *Diesel Plant Communication Package*
- *SCADA with internet access (continuous monitoring with 1 Hz and ten minute data acquisition)*



Microgrid examples

Sky view of SR Test Bed

Jeju Island Pilot Project - Korea

Microgrid examples

Tecnalia´s Laboratory – Bizkaia Spain

Power sources

- Diesel Generator (2x55KW)
- Microturbine (50Kw)
- Pacific Power sources (2x62.5kVA/50kW)
- PV single phase (0.6kW and 1.6kW)
- PV three phase (3.6kW)

Storage

- *Flywheel (250kVA)*
- *Ultracapacitor bank (48V 2.8Mj)*
- *Battery banks (48V-1925Ah and 24V-1120Ah)*

Communication

Ethernet, wi-fi, RS 485 & RS232, TCP/IP, Modbus

Microgrid examples

Kasabonika Example

Kasabonika Lake

Microgrid examples

Existent Microgrid:

- Diesel Generators: 1000, 600, 400 kW
  - Diesels have worked well for many years and are a well-known technology.
  - Many are familiar and comfortable with operational aspects.
  - Require regular attention (maintenance, service, replacement).
- Wind turbines: 3x10kW + 1(new)x30kW

Electrical issues:

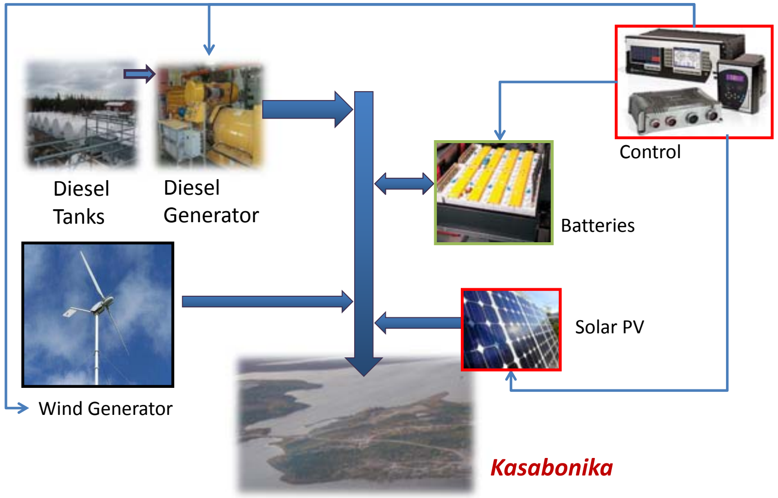
- Demand has already reached 90% electrical capacity.
- Additional 1.2MW gen. set on-site, but no funding available for its installation for at least 5 years.
- $10M Capital cost for expansion project (gen. set, 2x50,000 litre tanks, building, transformers, installation).
- All energy generation produces CO_2.

One diesel Gen Set

Diesel tank farm

Microgrid examples

Microgrid Proposal:



Diesel Tanks

Diesel Generator

Control

Batteries

Solar PV

Wind Generator

Kasabonika

Microgrid examples

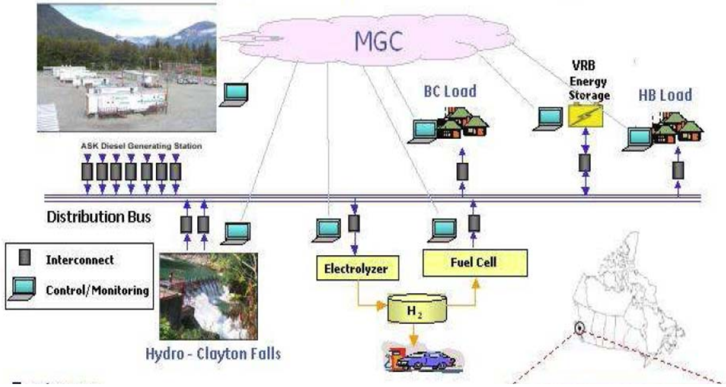
Bella Coola Example:

- Remote Microgrid 439 km north of Vancouver.
- Peak load: 3,800 kW
- RES: Hydro (700 + 1,420 kW)
- Diesel gen. sets: 7 (7,200 kW, less than 35% efficiency)
- Storage: Electrolyser (300 kW) and FC (125kW), and Vanadium Redox “flow” batteries (125 kW)
- 750kW power spikes from sawmill.

Microgrid examples

Bella Coola Example:

- A centralized controller (MGC) by GE dispatches the diesel generators using an MPC approach:



Microgrid Examples

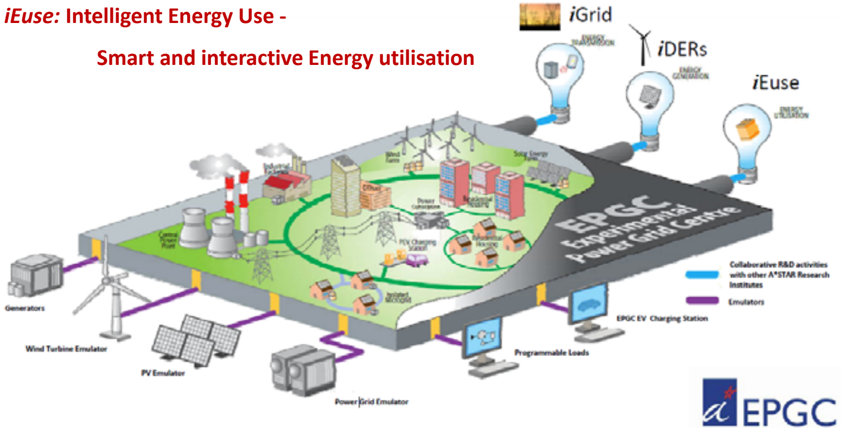
Experimental Power Grid Centre

iGrid: **Intelligent and decentralised power distribution networks**

iDERs: **Intelligent control and management of Distributed Energy Resources (DERs)**

iEuse: **Intelligent Energy Use -**

Smart and interactive Energy utilisation

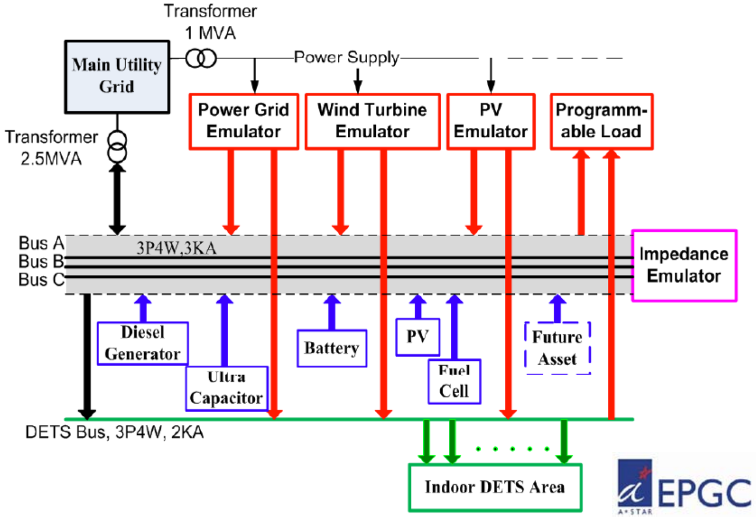


Microgrid Examples

Research facility housing experimental power grid
(Completed in Nov 2011)

Microgrid Examples

Flexible Infrastructure



Microgrids Examples

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Robben Island Green Microgrid

On-shore wind turbines on the Island.

SeaGen Tidal: Wave energy

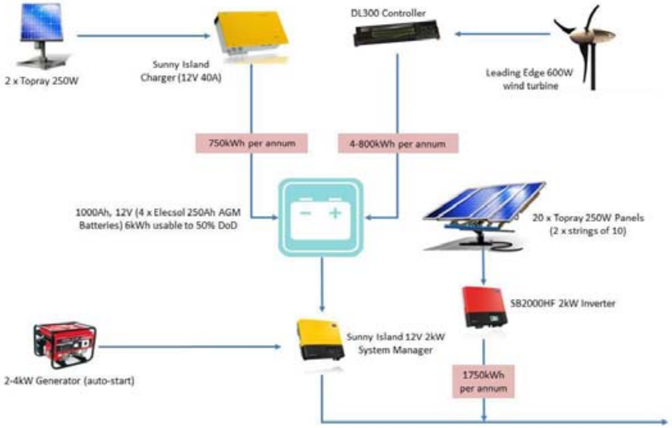
Solar Concentrators

Off-shore wind turbines surrounding the Island.

Microgrids examples

Robben Island Green Microgrid

3MW Hybrid Remote Energy System



Microgrids examples

DERlab's testing facilities

ICCS-NTUA - Microgrid laboratory

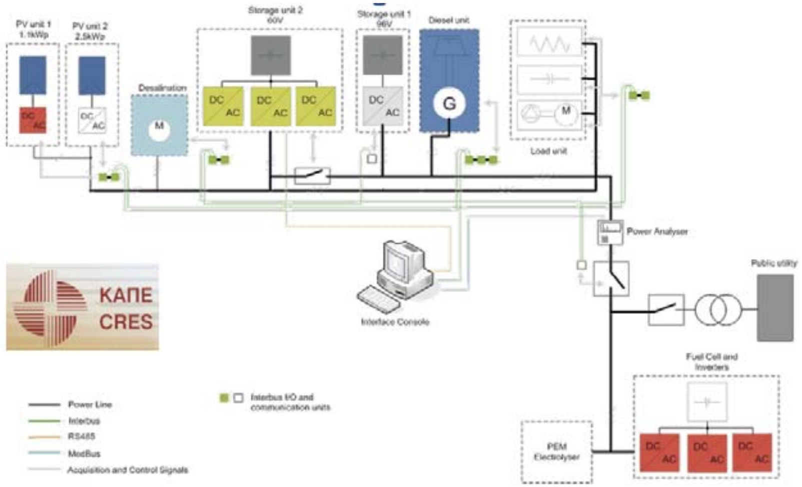
MultiAgent System (MAS)
Embedded system
Java apps and Windows CE based
Controllers used for I, V, f, P, Q measurements and to control 2 household loads through Power Line Communication (PLC).

Microgrid SCADA
LabVIEW and CoDeSys Software
Units Control via PLC (ON/OFF)
Programmable Load Curve

Microgrids examples

DERlab's testing facilities

CRES Microgrid



Microgrids examples

DERlab's testing facilities

Fraunhofer IWES

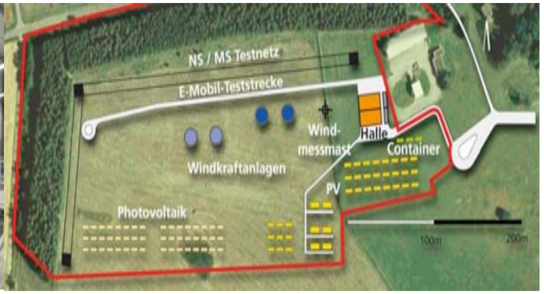
Test Centre for Smart Grids and Electromobility (SysTec)

Microgrids examples

DERlab's testing facilities

Test Centre for Smart Grids and Electromobility (SysTec)

Measurements of the static and dynamic electrical properties of DER units and networks
LV up to 1.25 MVA, MV up to 6 MVA
LV and MV test networks including generators and loads for connected and island operation
PV, Wind and Hybrid systems

Microgrids examples

DERlab's testing facilities

Microgrid Testing Facilities

Distributed Energy Resources Test Facility (DERTF)
Testing Microgrids up to 200kW
Grid Simulators, Load Banks, actual WT and PV

Energy Systems Integration Facility (ESIF)
Opens October 2012
Low Voltage (600V and Under) and MV (15kV and Under) test areas
Flexible connections for electrical, thermal, and fuel Infrastructure

National Wind Technology Center (NWTC)
7MW grid simulation access to MW scale wind turbines

Microgrids examples

DERlab's testing facilities

Flex Power Grid Lab (FPGLab)

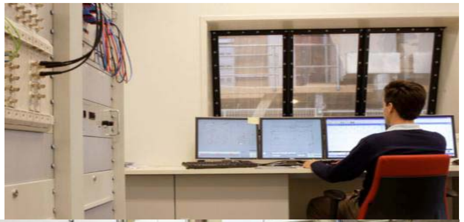
Microgrids examples

DERlab's testing facilities

Flex Power Grid Lab (FPGLab)

Fully programmable grid

- Voltage level up to 24 kV
- DC to 75 Hz frequency range
- Continuous power up to 1 MVA
- Up to >25th harmonics
- 4 Quadrant operation
- Synchronization with other source
- Controllable power exchange
- Adjustable loads (0.5MW, 1MVAr)




Microgrid Examples

Latin America Developments

Puertecitos
Under execution
Baja Califonia, MX

Huatacondo
Operative
Tarapacá, CH

Ollagüe
Design stage
Antofagasta, CH

Juan Fernández
Design stage
J. Fernández, CH

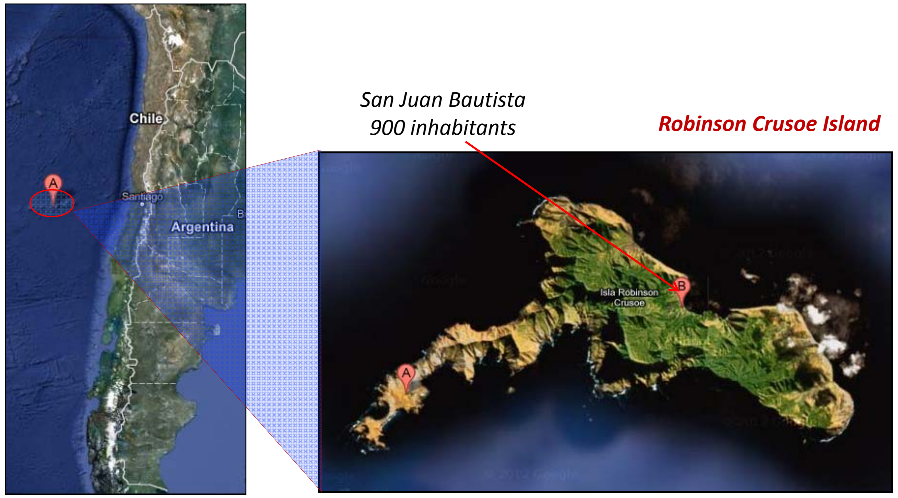
Silice Project
Pilot application
Bogotá, CO
“Smart Grids
and MGs
integration”

Isla Trinidad
Feasibility
Rio State, BR

Villa Cameron
Feasibility
Patagonia, CH

Microgrid Examples

Juan Fernández Island Project - Latin American Developments



San Juan Bautista
900 inhabitants

Robinson Crusoe Island

Microgrid Examples

27/02/10 Earthquake - Tsunami

Power supply interruption →
Health, communication, security

Microgrid Examples

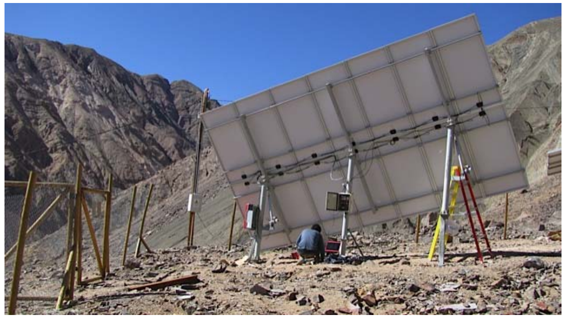
Juan Fernández Island Project - Latin American Developments

PV Siting

San Juan Bautista 900 inhabitants

Microgrid Examples

Huatacondo (PV tracking) Latin American Developments



- 2 linear actuators
- No sensors
- Centralized control
- Position feedback
- Intelligent relay local control
- Mechanical constraints considered on EMS

Paradigmatic Examples in Denmark

Kalundborg

➢Approximately 20,000 inhabitants, and its network is the most published example of ***Industrial Symbiosis***.

➢The history of Kalundborg Industrial Symbiosis activities began in 1961 when a project was developed and implemented to use surface water from Lake Tisso for a new oil refinery in order to save the limited supplies of ground water.

➢Kalundborg took the responsibility for building the pipeline, and a number of other collaborative projects were subsequently introduced while the number of partners gradually increased.

➢The material exchanges include:
- ▪conservation of natural and financial resources;
- ▪reduction in production,
- ▪material, energy, insurance and treatment costs and liabilities;
- ▪ improved operating efficiency; quality control;
- ▪improved health of the local population and public image;
- ▪and realisation of potential income through the sale of by-products and waste materials.

Paradigmatic Examples in Denmark

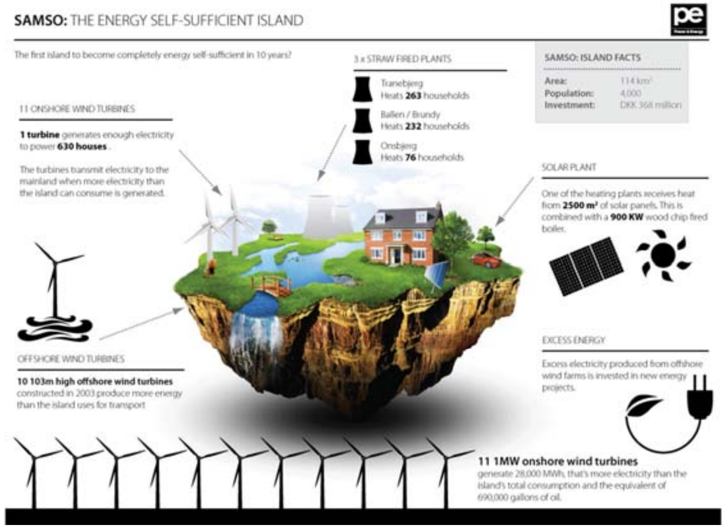
100% Renewable Energy: Samsø Island

- 4,000 people
- 22 villages
- 11 x 1MW-WT
- 10 x 2MW offshore WT

- The turbines supply more power than the residents need—
- Exports 80 million kWh wind-produced electricity annually

- Heating plant in Nordby relies on wood chips to create hot water and heat for the villagers. Many rural Samsingers also install highly efficient wood boilers in their homes if they cannot be connected to one of the district heating plants.
- 70 % of the island's heat and hot water needs

Paradigmatic Examples in Denmark



SAMSO: THE ENERGY SELF-SUFFICIENT ISLAND

The first island to become completely energy self-sufficient in 10 years?

3 x STRAW FIRED PLANTS

Tranebjerg
Heats **263** households

Ballen / Brundy
Heats **232** households

Onsbjerg
Heats **76** households

SAMSO: ISLAND FACTS

Area:	114 km²
Population:	4,000
Investment:	DKK 368 million

11 ONSHORE WIND TURBINES

1 turbine generates enough electricity to power **630 houses**.

The turbines transmit electricity to the mainland when more electricity than the island can consume is generated.

SOLAR PLANT

One of the heating plants receives heat from **2500 m²** of solar panels. This is combined with a **900 KW** wood chip fired boiler.

OFFSHORE WIND TURBINES

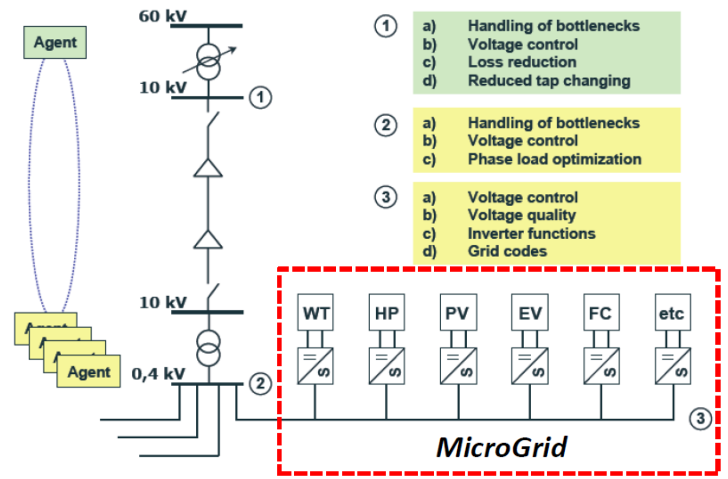
10 103m high offshore wind turbines constructed in 2003 produce more energy than the island uses for transport

EXCESS ENERGY

Excess electricity produced from offshore wind farms is invested in new energy projects.

11 1MW onshore wind turbines generate 28,000 MWh, that's more electricity than the island's total consumption and the equivalent of 690,000 gallons of oil.

Denmark Grid Concept



① a) Handling of bottlenecks
b) Voltage control
c) Loss reduction
d) Reduced tap changing

② a) Handling of bottlenecks
b) Voltage control
c) Phase load optimization

③ a) Voltage control
b) Voltage quality
c) Inverter functions
d) Grid codes

New low voltage feeder with cell-controller technical functionalities. Source: Energinet.dk

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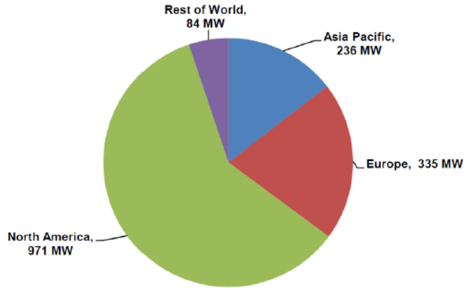
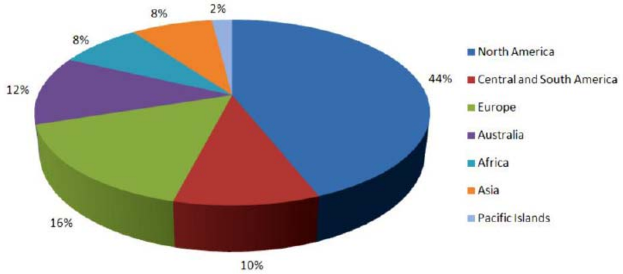
Microgrid capacity by region

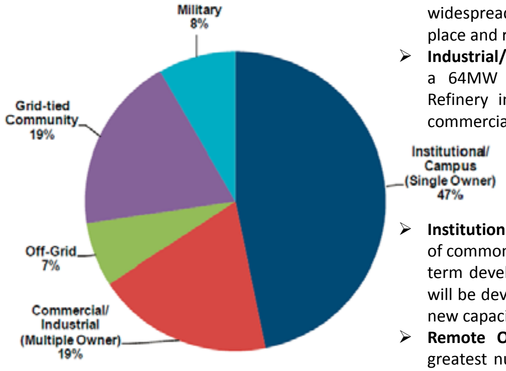
MicroGrid capacity by region, world markets (4th Q, 2011), source: Pike Research



MicroGrid in the world. Source: CSIRO 2011



MicroGrid Market Segments



Market Sector Breakdown. Source: Pike Research.

- **Community/Utility MicroGrids:** Includes residential customers. This class of MicroGrids will not achieve widespread commercial acceptance until standards are in place and regulatory barriers are removed.
- **Industrial/Commercial MicroGrids**: The first MG in USA was a 64MW facility constructed in 1995 at the Whittling Refinery in Indiana. Nowadays, Japan is a leader in the commercial/industrial sector.
- **Institutional/Campus MicroGrids**: Because of the advantage of common ownership, this class of MGs offers the best near-term development opportunity. In USA 40% of future MGs will be developed in this market segment, adding 940MW of new capacity valued at $2.76 billion by 2015.
- **Remote Off-Grid Systems:** This segment represents the greatest number of MicroGrids currently operating globally, but it has the smallest average capacity. The largest growth sector is solar photovoltaics (PV).
- **Military MicroGrids:** They are integrating renewable distributed energy generation as a way to secure power supply without being dependent on any supplied fuel.

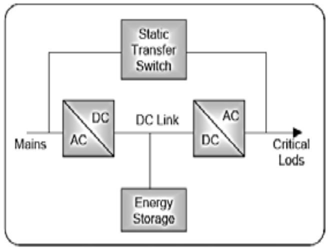
Outline

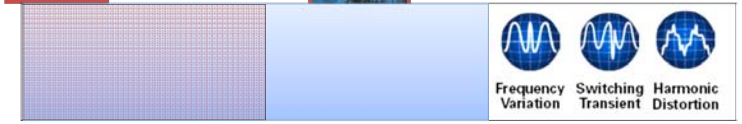
- Distributed power systems
- Microgrid Definition
- Microgrid Configurations
- Ex of Microgrids
- UPS

UPS (Uninterruptible Power Supplies)

Is a device that tries to maintain a continuous supply of electric power to the connected loads by supplying power from a separated source (storage) when the mains fails

- Main types of UPS:
  - *Static: based on power electronics*
  - *Dynamic: based on motor/generator engines*
  - *Hybrid: mix between static and dynamic*





Future Grids

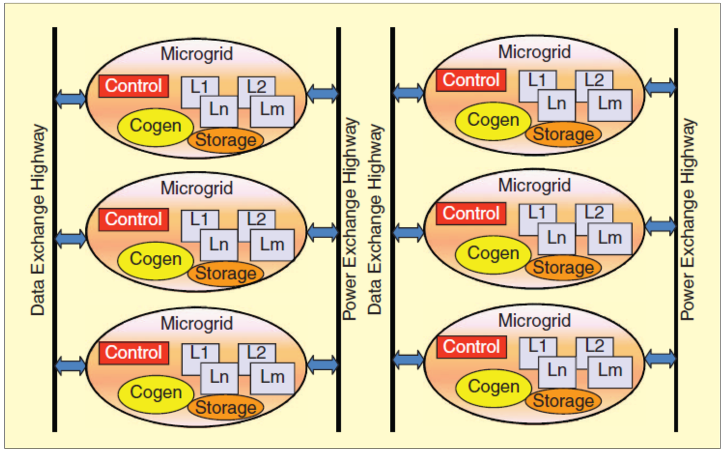
Smartgrid compared with the existing grid

Existing Grid	Intelligent Grid
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

H. Farhangi. The path of the Smart Grid

Future Grids

Future clusters of microgrids



H. Farhangi. The path of the Smart Grid

Conclusions

- Microgrids taking importance for integrate renewable or nonconventional power sources
- Isolated Microgrids can be interesting for rural areas of islands
- Now can be extended for grid connected and island modes: flexible Microgrids
- There are demonstrative, research, and real applications of Microgrids in the whole world. Governments are interested of this new concept
- Smart grid concept can be linked to Microgrids: next questions are who to interconnect Microgrids and which will be the information to exchange between the operator and the Microgrid
- The interesting sectors in the market are wide:
  - Critical safe Microgrids (hospital, servers, industrial processes)
  - Emerging countries: China and India
  - Development countries (Africa and South America)
  - Isolated places with potential energy resources

Conclusions

- To introduce Microgrids, it is necessary:
  - Change of the grid codes
  - New standards
  - Proper communication systems (PLC, RF) and standardization
  - More research and real interdisciplinary
  - Promote them economic and social terms
- Distributed storage energy systems allows:
  - Global efficiency
  - Reliability
  - UPS functionalities
  - Active power balancing
  - Flexibility in WT and PV parks, but also in domestic renewable energy application
- The use of distributed storage energy systems allows the integration of renewable energy systems but also in new energy vectors like fuels cells and hydrogen-based technologies

Control, Modeling, and Implementation of Microgrids

Ernane Coelho, Prof. Universidade Federal de Uberlândia, Brasil

Control, Modeling, and Implementation of Microgrids

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ernane@ufu.br

Outline

Introduction – Distributed Generation Systems and Microgrids

What is Distributed Generation Systems?

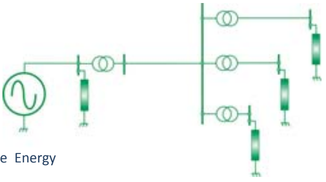
Large electrical generation power plant → Distributed Loads

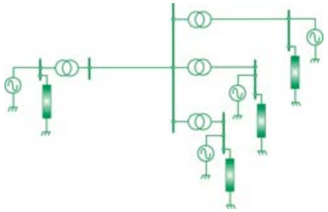
↓

Distributed Sources → Distributed Loads

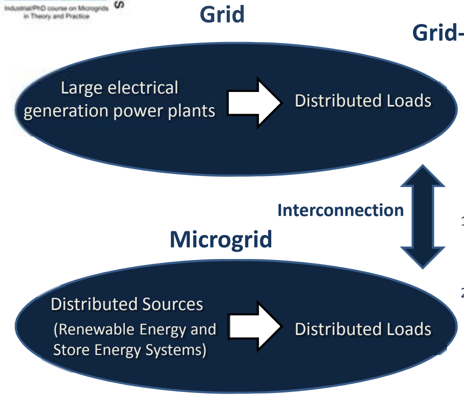
Why?

The advent of Alternative Energy
- Solar energy
- Wind energy
- Fuel Cell
- Gas turbine





Introduction – Distributed Generation Systems and Microgrids



Grid

Large electrical generation power plants → Distributed Loads

Interconnection

Microgrid

Distributed Sources (Renewable Energy and Store Energy Systems) → Distributed Loads

Grid-connected inverters:

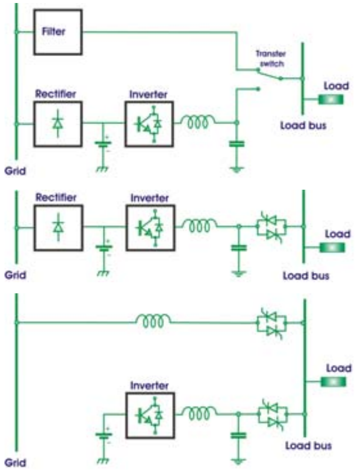
- **Current-controlled mode** [1]
- **Voltage-controlled mode** [2]

1. Supplied by renewable energy. An anti-islanding scheme is necessary since the islanded operation is not possible (no voltage control loop).
2. A dispatchable source is necessary. Islanded operation is possible. Generally the droop control method is used.

A change of paradigm: the final users are able to generate, store, control, and manage part of the energy that they consume . They are a part of the grid. **[Guerrero, 2011]**

2. Parallel-connected Inverter Applications

→ UPS Systems



Types of UPS:

Off-line or Stand-by

On-line or double conversion

Line-Interactive *

***Grid-connected Inverter**

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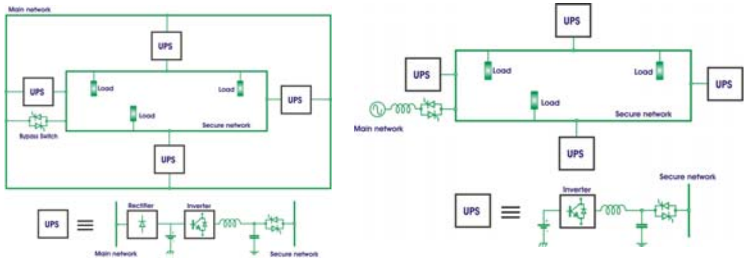
2. Parallel-connected Inverter Applications

UPS Distributed Systems [Chandorkar, 1994]



On-line distributed UPS system Line-interactive distributed UPS system

- The main point was to enhance the system reliability by the addition of redundancy;
- With the advent of alternative energy sources, the idea of a safe network led to the microgrids;
- The parallel connection is the way to integrate the alternative sources into the grid;
- The UPS function would be analogous to the microgrid stand-alone operation.

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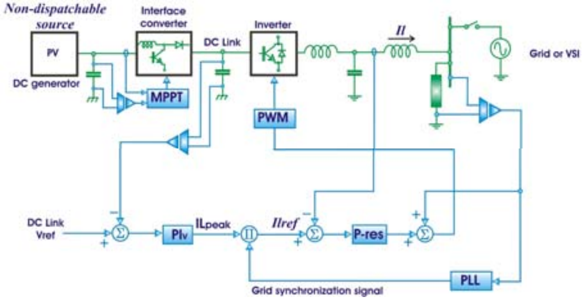
3. Control schemes for Parallel-connected Inverter Operation

3.1. Current Controlled VSI



- The DC link voltage is regulated by the inverter controller;
- There is no output voltage control loop;
- It can't operate in islanded mode without an addition control strategy and a storage energy system;
- The PV system dynamics is suitably followed by the inverter controller.

---

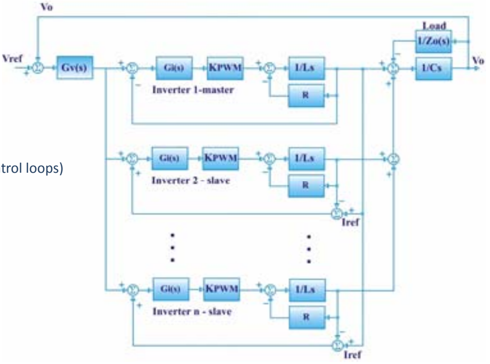
3. Control schemes for Parallel-connected Inverter Operation

3.2. Voltage Controlled VSI
  - With communication;
  - Without communication.

3. Control schemes for Parallel-connected Inverter Operation

3.2. Voltage Controlled VSI

- With communication



Master-slave
(combined voltage and current control loops)

- Absence of redundancy (dependency of the master);
- The dynamics of the slaves is affected by the dynamics of the master;
- Easy expansion by the addition of slaves.

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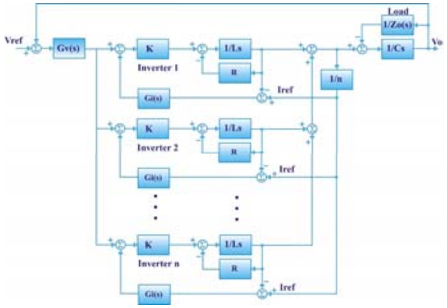
3. Control schemes for Parallel-connected Inverter Operation

3.2. Voltage Controlled VSI

- With communication



Central-Limit Control [Siri and Lee,1990]

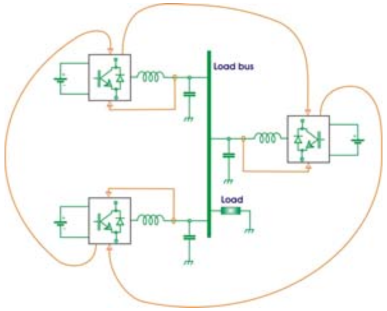
- This scheme was originally developed for dc-dc converters, but it can be applied to inverter applications
- Identical units;
- Dependency of the central control (reference current);
- The measurement of the total load current is difficult when the loads are spread over a large area.

---

3. Control schemes for Parallel-connected Inverter Operation

3.2. Voltage Controlled VSI

- With communication



Circular Chain Control [Wu et al., 1998]

- Identical units (internal current loop and external voltage loop);
- The circular chain is implemented on the internal current loop;
- The ring disruption leads the system to blackout..

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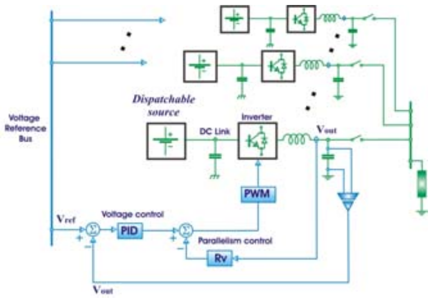
3. Control schemes for Parallel-connected Inverter Operation

3.2. Voltage Controlled VSI

- With communication



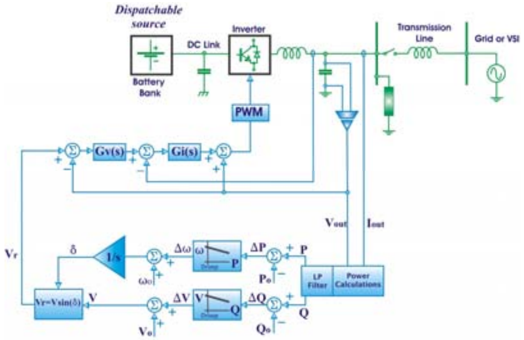
Parallelism Control [Lazzarin et al., 2013]

- Identical units;
- Hot swapping capability.
- Dependency of the voltage reference bus (It is not a system state, one way signal);

3. Control schemes for Parallel-connected Inverter Operation

3.2. Voltage Controlled VSI

- Without communication



Conventional Droop Control Method

- No dependency of communication between units;
- Poor dynamics compared to the other schemes (feedback of the average power);
- The inverter emulates the behavior of a synchronous machine.

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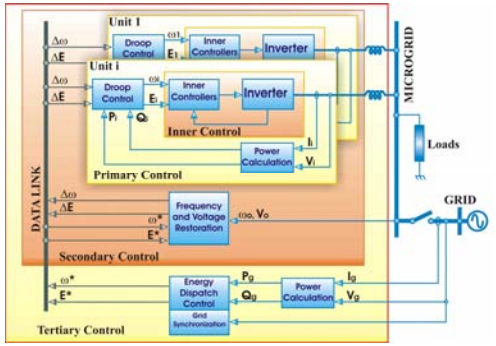
4. Microgrid Small-Signal Modeling

4.1. Microgrid Control Hierarchy



- **Primary Control** - it keeps the power flow stable based on frequency and voltage droops using only local measurements. No communication link is necessary.
- **Secondary Control** - it provides the frequency and voltage restoration after load transients. A low bandwidth communication is necessary.
- **Tertiary Control** - it controls the power exchange between the grid and the microgrid. **[Guerrero, 2011]**

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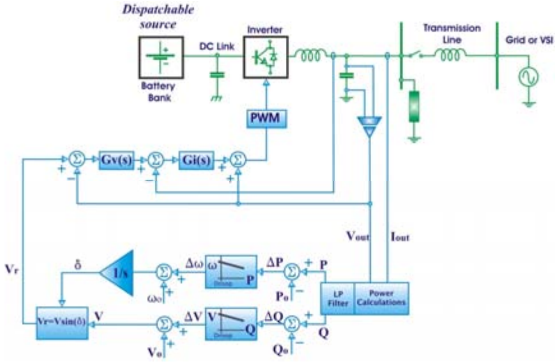
4. Microgrid Small-Signal Modeling

4.2. Primary Control



Conventional Droop Control Method

Droop Method is derived from Electrical Power System Control

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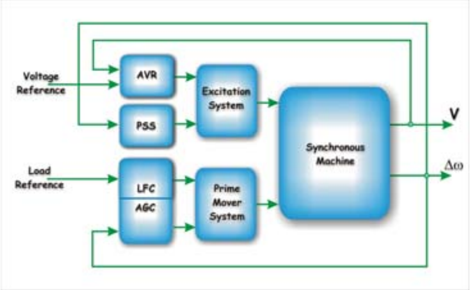
4. Microgrid Small-Signal Modeling

4.2. Primary Control - Analogy with the electrical power system



Electrical Power System Controllers

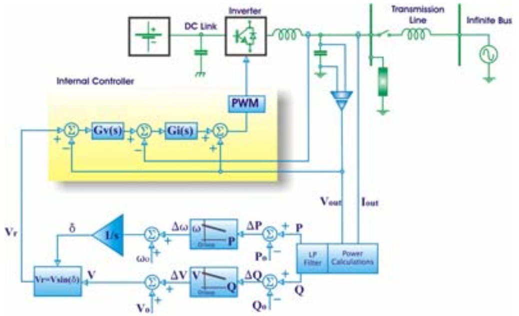
AVR - Automatic Voltage Regulation (voltage droop)

PSS - Power System Stabilizer

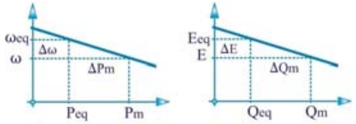
LFC - Load-Frequency Control } (frequency droop)

AGC - Automatic Generation Control

4.3. Small-Signal Analysis of a Grid-connected Inverter



- The Inverter dynamics is neglected;
- The grid is considered as a infinite bus.



Droop equations:

$$\omega = \omega_{eq} - k_p \Delta P_m$$

$$E = E_{eq} - k_v \Delta Q_m$$

4.3. Small-Signal Analysis of a Grid-connected Inverter

Active and reactive power through a transmission line:

$$P = \frac{1}{R^2 + X^2} \quad (RE^2 - REV\cos\delta + XEV\sin\delta)$$

$$Q = \frac{1}{R^2 + X^2} \quad (XE^2 - XEV\cos\delta - REV\sin\delta)$$

Linearization:

Considering only the first order derivative term of the Taylor series!

$$f(x) = f(a) + \frac{\boldsymbol{f'(a)}}{\boldsymbol{1!}}(\boldsymbol{x} - \boldsymbol{a}) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3$$

$$\Delta f = f(x) - f(a) = \frac{\boldsymbol{f'(a)}}{\boldsymbol{1!}}(\boldsymbol{x} - \boldsymbol{a})$$

$$\Delta x = (x - a)$$

Equilibrium point defined by: $\delta_{eq}, E_{eq}, V_{eq}$

$$\Delta\omega = \frac{\partial\omega}{\partial P} \quad \Delta P_m$$

$$\Delta P = \frac{\partial P}{\partial E}\Delta E + \frac{\partial P}{\partial\delta}\Delta\delta$$

$$\Delta E = \frac{\partial E}{\partial Q} \quad \Delta Q_m$$

$$\Delta Q = \frac{\partial Q}{\partial E}\Delta E + \frac{\partial Q}{\partial\delta}\Delta\delta$$

4.3. Small-Signal Analysis of a Grid-connected Inverter

$$\Delta\omega = -k_p \Delta P_m$$

$$\Delta P = k_{pe}\Delta E + k_{pd}\Delta\delta$$

$$\Delta E = -k_v \Delta Q_m$$

$$\Delta Q = k_{qe}\Delta E + k_{qd}\Delta\delta$$

$$k_{pe} = \frac{1}{R^2 + X^2} \quad (2RE_{eq} - RV_{eq}\cos\delta_{eq} + XV_{eq}\sin\delta_{eq})$$

$$k_{pd} = \frac{1}{R^2 + X^2} \quad (RE_{eq}V_{eq}\sin\delta_{eq} + XE_{eq}V_{eq}\cos\delta_{eq})$$

$$k_{qe} = \frac{1}{R^2 + X^2} \quad (2XE_{eq} - XV_{eq}\cos\delta_{eq} - RV_{eq}\sin\delta_{eq})$$

$$k_{qd} = \frac{1}{R^2 + X^2} \quad (XE_{eq}V_{eq} sen\delta_{eq} - RE_{eq}V_{eq}\cos\delta_{eq})$$

4.3. Small-Signal Analysis of a Grid-connected Inverter

Power measuring filters :

$$\Delta P_m(s) = \frac{\omega_f}{s + \omega_f}\Delta P(s)$$

$$\Delta Q_m(s) = \frac{\omega_f}{s + \omega_f}\Delta Q(s)$$

$$\Delta\omega(s) = -\frac{k_p\omega_f}{s + \omega_f} \quad \left(k_{pe}\Delta E(s) + k_{pd}\Delta\delta(s)\right)$$

$$\Delta E(s) = -\frac{k_p\omega_f}{s + \omega_f} \quad \left(k_{qe}\Delta E(s) + k_{qd}\Delta\delta(s)\right)$$

4.3. Small-Signal Analysis of a Grid-connected Inverter

Behavior of the angle δ around the equilibrium point $\delta eq,\ Eeq,\ Veq$:

$$\boxed{s^3\Delta\delta(s) + a\,s^2\Delta\delta(s) + b\,s\Delta\delta(s) + c\,\Delta\delta(s) = 0}$$

$$\boxed{a = \left(2 + k_v k_{qe}\right)\omega_f}$$

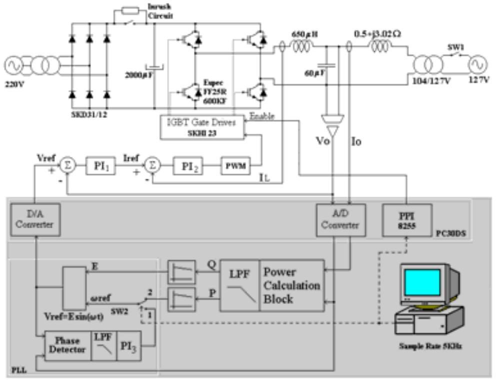
$$\boxed{b = \left(k_p k_{pd} + k_v k_{qe}\omega_f + \omega_f\right)\omega_f}$$

$$\boxed{c = \left(k_{pd} + k_v k_{pd} k_{qe} - k_v k_{pe} k_{qd}\right) k_p \omega_f^2}$$

4.3. Small-Signal Analysis of a Grid-connected Inverter

Experimental Results

Variable	Value	Unit
Line impedance	0.5+j3.02	Ω
ω_f	75.4	rd/s
ξ	0.7	
k_p	0.005	rd/s/W
k_v	0.005	V/VAR
S (grid)	500+j250	VA
S (inverter)	514+j337	VA
Veq	104	V (rms)
Eeq	114	V (rms)
ω	377	rd/s
$\Delta\delta$	0.1165	rd



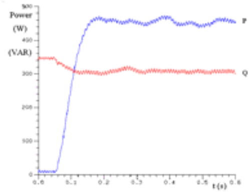
[Coelho et al., 1999]

4.3. Small-Signal Analysis of a Grid-connected Inverter

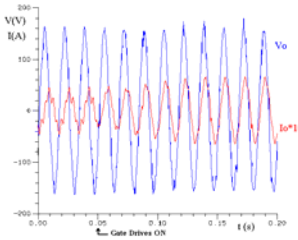
Experimental Results - Test 1

kp =0.005 rad/s/W

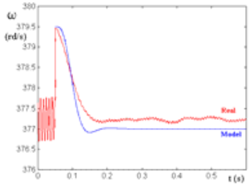
kv =0.005 V/VAr



Active and Reactive Power



Output Voltage and current



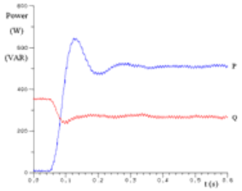
Inverter frequency (real and model)

4.3. Small-Signal Analysis of a Grid-connected Inverter

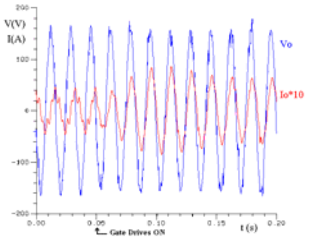
Experimental Results - Test 2

kp =0.01 rad/s/W

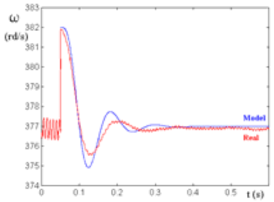
kv =0.01 V/VAr



Active and reactive power



Output voltage and current

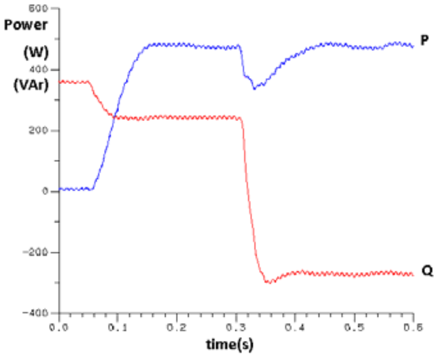


Inverter frequency (real and model)

4.3. Small-Signal Analysis of a Grid-connected Inverter

Experimental Results - Test 3

kp =0.005 rad/s/W
kv =0.005 V/VAr



- The Reactive power reference is changed from 250 to -250 VAr at t=0.3s
- P and Q fluxes are not absolutely decoupled.

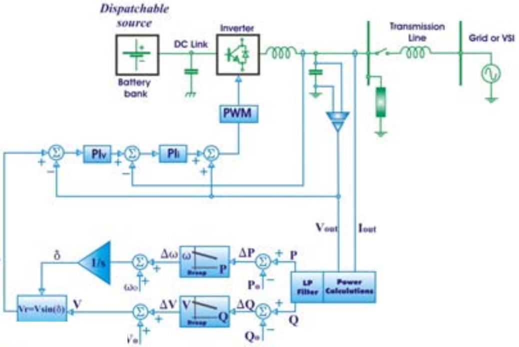
4.4. Small-Signal Analysis of a Stand-alone System

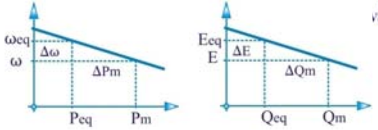
Scheme of each unit

Droop equations:

$$\omega = \omega_{eq} - k_p \Delta P_m$$

$$E = E_{eq} - k_v \Delta Q_m$$





- The Inverter dynamics is neglected.

4.4. Small-Signal Analysis of a Stand-alone System

Power measuring filters:

$$P_m(s) = \frac{\omega_f}{s+\omega_f} \quad P(s)$$

$$Q_m(s) = \frac{\omega_f}{s+\omega_f} \quad P(s)$$

Linearized droop control equations:

$$\Delta\dot{\omega} = -\omega_f \Delta\omega - k_p \omega_f \Delta P$$

$$\Delta\dot{E} = -\omega_f \Delta E - k_v \omega_f \Delta Q$$

Linearizing the expressions for δ and E :

$$\delta = \arctan\left(\frac{e_q}{e_d}\right)$$

$$\vec{E} = e_d + j\, e_q$$

$$E = \left|\vec{E}\right| = \sqrt{e_d^2 + e_q^2}$$

$$\Delta\delta = m_d \Delta e_d + m_q \Delta e_q$$

$$m_d = -\frac{e_q}{e_d^2 + e_q^2}$$

$$m_q = \frac{e_d}{e_d^2 + e_q^2}$$

$$\Delta E = n_d \Delta e_d + n_q \Delta e_q$$

$$n_d = \frac{e_d}{\sqrt{e_d^2 + e_q^2}}$$

$$n_q = \frac{e_q}{\sqrt{e_d^2 + e_q^2}}$$

4.4. Small-Signal Analysis of a Stand-alone System

State equation for each i-th inverter:

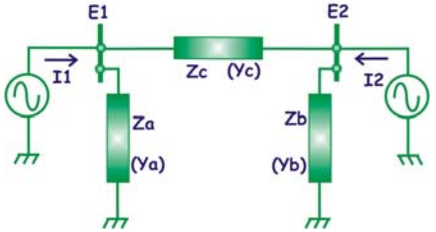
$$\begin{bmatrix} \Delta\dot{\omega}_i \\ \Delta\dot{e}_{di} \\ \Delta\dot{e}_{qi} \end{bmatrix} = [M_i] \begin{bmatrix} \Delta\omega_i \\ \Delta e_{di} \\ \Delta e_{qi} \end{bmatrix} + [C_i] \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}$$

For 2 inverters:
sixth-order state equation

$$\begin{bmatrix} \Delta\dot{\omega}_1 \\ \Delta\dot{e}_{d1} \\ \Delta\dot{e}_{q1} \\ \Delta\dot{\omega}_2 \\ \Delta\dot{e}_{d2} \\ \Delta\dot{e}_{q2} \end{bmatrix} = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \begin{bmatrix} \Delta\omega_1 \\ \Delta e_{d1} \\ \Delta e_{q1} \\ \Delta\omega_2 \\ \Delta e_{d2} \\ \Delta e_{q2} \end{bmatrix} + \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \end{bmatrix}$$

$$[M_i] = \begin{bmatrix} -\omega_f & & & 0 \\ \frac{n_q}{m_d n_q - m_q n_d} & \frac{m}{m_d n} & & \frac{k_v m_q \omega_f}{m_d n_q - m_q n_d} \\ \frac{n_d}{m_q n_d - m_d n_q} & \frac{m_d n_d \omega_f}{m_q n_d - m_d n_q} & \frac{m_d n_q \omega_f}{m_q n_d - m_d n_q} \end{bmatrix} \quad \begin{bmatrix} 0 & \frac{k_v m_d \omega_f}{m_q n_d - m_d n_q} \end{bmatrix}$$

4.4. Small-Signal Analysis of a Stand-alone System



Considering only two inverters:

$$\begin{bmatrix}\vec{I}_1\\ \vec{I}_2\end{bmatrix}=\begin{bmatrix}Y_a+Y_c & -Y_c\\ -Y_c & Y_c+Y_c\end{bmatrix}\begin{bmatrix}\vec{E}_1\\ \vec{E}_2\end{bmatrix}$$

$$\begin{bmatrix}i_{d1}\\ i_{q1}\\ i_{d2}\\ i_{q2}\end{bmatrix}=\begin{bmatrix}G_{11} & -B_{11} & G_{12} & -B_{12}\\ B_{11} & G_{11} & B_{12} & G_{12}\\ G_{21} & -B_{21} & G_{22} & -B_{22}\\ B_{21} & G_{21} & B_{22} & G_{22}\end{bmatrix}\begin{bmatrix}e_{d1}\\ e_{q1}\\ e_{d2}\\ e_{q2}\end{bmatrix}$$

Symbolic nodal equation : $\boxed{[\Delta i]=[Y_s]\quad[\Delta e]}$

4.4. Small-Signal Analysis of a Stand-alone System

Power Calculations:

$$\boxed{\begin{aligned}P_i &= e_{di}i_{di}+e_{qi}i_{qi}\\ Q_i &= e_{di}i_{qi}-e_{qi}i_{di}\end{aligned}}$$

Considering 2 units, and linearizing for a given equilibrium point:

$$\begin{bmatrix}\Delta P_1\\ \Delta Q_1\\ \Delta P_2\\ \Delta Q_2\end{bmatrix}=\begin{bmatrix}i_{d1} & i_{q1} & 0 & 0\\ -i_{q1} & i_{d1} & 0 & 0\\ 0 & 0 & i_{d2} & i_{q2}\\ 0 & 0 & -i_{q2} & i_{d2}\end{bmatrix}\begin{bmatrix}\Delta e_{d1}\\ \Delta e_{q1}\\ \Delta e_{d2}\\ \Delta e_{q2}\end{bmatrix}+\begin{bmatrix}e_{d1} & e_{q1} & 0 & 0\\ e_{q1} & -e_{d1} & 0 & 0\\ 0 & 0 & e_{d2} & e_{q2}\\ 0 & 0 & e_{q2} & -e_{d2}\end{bmatrix}\begin{bmatrix}\Delta i_{d1}\\ \Delta i_{q1}\\ \Delta i_{d2}\\ \Delta i_{q2}\end{bmatrix}$$

Symbolically:

$\boxed{[\Delta S]=[I_s][\Delta e]+[E_s][\Delta_i]}$

Using the nodal equation:

$\boxed{[\Delta S]=\left([I_s]+[E_s][Y_s]\right)\quad[\Delta e]}$

4.4. Small-Signal Analysis of a Stand-alone System

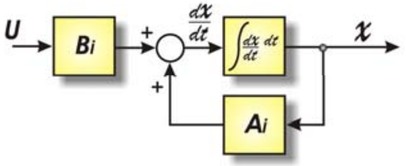
$$\begin{bmatrix}\Delta\dot{\omega}_1\\ \Delta\dot{e}_{d1}\\ \Delta\dot{e}_{q1}\\ \Delta\dot{\omega}_2\\ \Delta\dot{e}_{d2}\\ \Delta\dot{e}_{q2}\end{bmatrix}=\begin{bmatrix}M_1 & 0\\ 0 & M_2\end{bmatrix}\begin{bmatrix}\Delta\omega_1\\ \Delta e_{d1}\\ \Delta e_{q1}\\ \Delta\omega_2\\ \Delta e_{d2}\\ \Delta e_{q2}\end{bmatrix}+\begin{bmatrix}C_1 & 0\\ 0 & C_2\end{bmatrix}\begin{bmatrix}\Delta P_1\\ \Delta Q_1\\ \Delta P_2\\ \Delta Q_2\end{bmatrix}$$

Symbolically :

$\boxed{[\Delta\dot{X}]=[M_s][\Delta X]+[C_s][\Delta S]}$

$$\boxed{\dot{x}=A_i x+B_i U}$$

$$\Delta x=\begin{bmatrix}\Delta\omega_1\\ \Delta e_{d1}\\ \Delta e_{q1}\\ \Delta\omega_2\\ \Delta e_{d2}\\ \Delta e_{q2}\end{bmatrix}$$



4.4. Small-Signal Analysis of a Stand-alone System

$$U=\Delta S=\begin{bmatrix}\Delta P_1\\ \Delta Q_1\\ \Delta P_2\\ \Delta Q_2\end{bmatrix}$$

$$\begin{bmatrix}\Delta P_1\\ \Delta Q_1\\ \Delta P_2\\ \Delta Q_2\end{bmatrix}=\begin{bmatrix}i_{d1} & i_{q1} & 0 & 0\\ -i_{q1} & i_{d1} & 0 & 0\\ 0 & 0 & i_{d2} & i_{q2}\\ 0 & 0 & -i_{q2} & i_{d2}\end{bmatrix}\begin{bmatrix}\Delta e_{d1}\\ \Delta e_{q1}\\ \Delta e_{d2}\\ \Delta e_{q2}\end{bmatrix}+\begin{bmatrix}e_{d1} & e_{q1} & 0 & 0\\ e_{q1} & -e_{d1} & 0 & 0\\ 0 & 0 & e_{d2} & e_{q2}\\ 0 & 0 & e_{q2} & -e_{d2}\end{bmatrix}\begin{bmatrix}\Delta i_{d1}\\ \Delta i_{q1}\\ \Delta i_{d2}\\ \Delta i_{q2}\end{bmatrix}$$

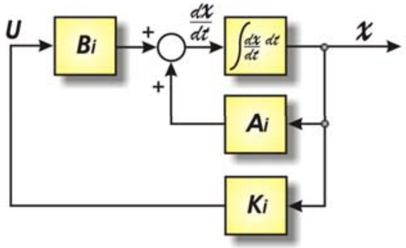
$\boxed{[\Delta S]=[I_s][\Delta e]+[E_s][\Delta_i]}$

$\boxed{[\Delta i]=[Y_s]\quad[\Delta e]}$

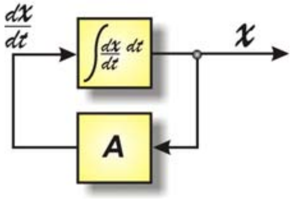
$\boxed{[\Delta S]=\left([I_s]+[E_s][Y_s]\right)\quad[\Delta e]}$

$\boxed{[\Delta e]=[K_e]\quad[\Delta x]}$

$$[K_e]=\begin{bmatrix}0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 0 & 1\end{bmatrix}$$



4.4. Small-Signal Analysis of a Stand-alone System



Small-signal model: (homogenous equation) [Coelho et al., 2002]

$$\left[\Delta\dot{X}\right]=[A][\Delta X]$$

$$[X]=[X]_{eq}+e^{[A]t}[\Delta X(0)]$$

Where: $[A]=[M_s]+[C_s]\left([I_s]+[E_s][Y_s]\right)[K_e]$

$[X]_{eq}$ State vector at equilibrium point or steady state

$[\Delta X(0)]$ Initial condition at the neighborhood of equilibrium point

Considering the model, it is possible to use an optimization tool to the system design [Godoy et al., 2012]

4.4. Small-Signal Analysis of a Stand-alone System

Simulation Results - Test 1

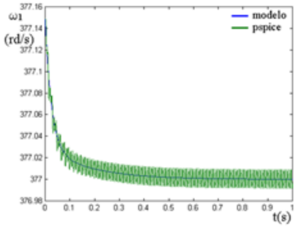
Eigenvalues:

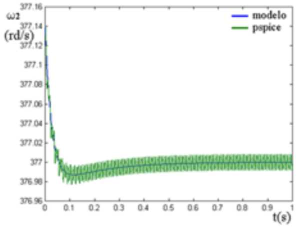
$$\begin{aligned}\lambda_1 &= 0.0\\ \lambda_2 &= -5.51\\ \lambda_3 &= -32.17\\ \lambda_4 &= -37.70\\ \lambda_5 &= -37.75\\ \lambda_6 &= -39.14\end{aligned}$$

Redundant state

- All poles are real

Variable	**Valuer**	**Unit**
Transmission Line (Zc)	0.2+j3.1	Ω
Local load – inverter 1 (Za)	25.7+j27.2	Ω
Local load – inverter 2 (Zb)	52+j9	Ω
k_p	0.0005	rad/s/W
k_v	0.0005	V/VAr
ω_f	37.7	rd/s
S_1	298+j187	VA
S_2	280+j180	VA
E_1	127+j0	V (rms)
E_2	130.3-j1.2	V (rms)
I_1	2.3-j1.5	A(rms)
I_2	2.1-j1.4	A(rms)
ω	377	rd/s





4.4. Small-Signal Analysis of a Stand-alone System

Simulation Results - Test 2

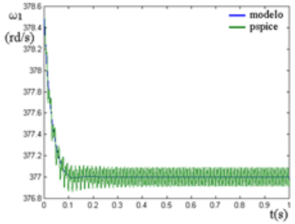
Eigenvalues:

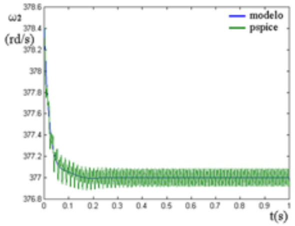
$$\begin{aligned}\lambda_1 &= 0.0\\ \lambda_2 &= -18.8+j37.7\\ \lambda_3 &= -18.8-j37.7\\ \lambda_4 &= -37.70\\ \lambda_5 &= -38.20\\ \lambda_6 &= -52.10\end{aligned}$$

Redundant state

Complex conjugate pair

Variable	**Valuer**	**Unit**
Transmission Line (Zc)	0.2+j3.1	Ω
Local load – inverter 1 (Za)	25.7+j27.2	Ω
Local load – inverter 2 (Zb)	52+j9	Ω
k_p	0.005	rad/s/W
k_v	0.005	V/VAr
ω_f	37.7	rd/s
S_1	298+j187	VA
S_2	280+j180	VA
E_1	127+j0	V (rms)
E_2	130.3-j1.2	V (rms)
I_1	2.3-j1.5	A(rms)
I_2	2.1-j1.4	A(rms)
ω	377	rd/s





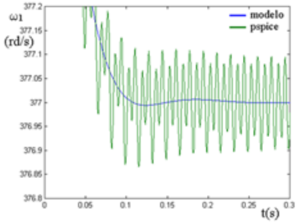
4.4. Small-Signal Analysis of a Stand-alone System

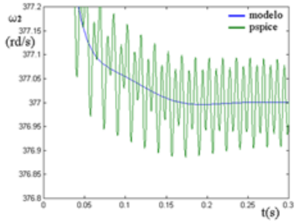
Simulation Results - Test 1 (zoom)

Eigenvalues:

$$\begin{aligned}\lambda_1 &= 0.0\\ \lambda_2 &= -18.8+j37.7\\ \lambda_3 &= -18.8-j37.7\\ \lambda_4 &= -37.70\\ \lambda_5 &= -38.20\\ \lambda_6 &= -52.10\end{aligned}$$

Variable	**Valuer**	**Unit**
Transmission Line (Zc)	0.2+j3.1	Ω
Local load – inverter 1 (Za)	25.7+j27.2	Ω
Local load – inverter 2 (Zb)	52+j9	Ω
k_p	0.005	rad/s/W
k_v	0.005	V/VAr
ω_f	37.7	rd/s
S_1	298+j187	VA
S_2	280+j180	VA
E_1	127+j0	V (rms)
E_2	130.3-j1.2	V (rms)
I_1	2.3-j1.5	A(rms)
I_2	2.1-j1.4	A(rms)
ω	377	rd/s



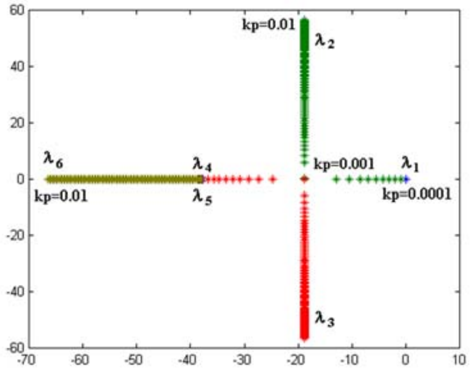


4.4. Small-Signal Analysis of a Stand-alone System

Parametric analysis: ***droop gain variation***

Root locus

$0.0001 < k_p = k_v < 0.01$

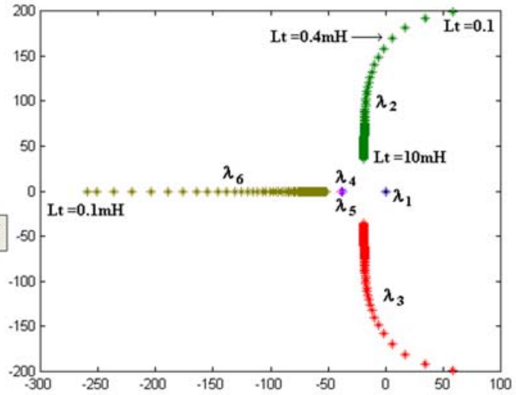


4.4. Small-Signal Analysis of a Stand-alone System

Parametric analysis: ***transmission line inductance variation***

Root locus

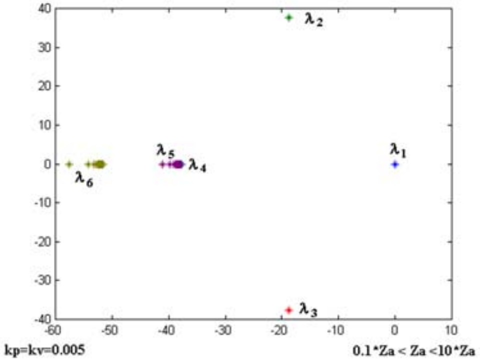
$0.1 < L_T < 10mH$



4.4. Small-Signal Analysis of a Stand-alone System

Root locus

$0.1\,Z_a < Z_a < 10\,Z_a$

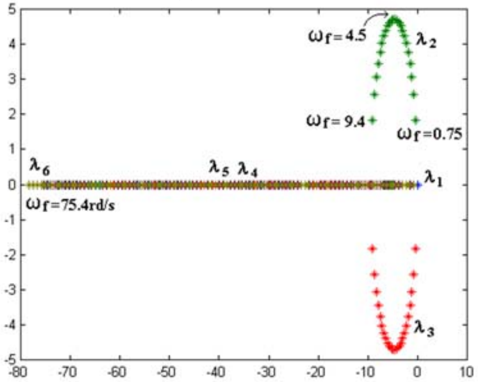


4.4. Small-Signal Analysis of a Stand-alone System

Parametric analysis: ***variation of the cut-off frequency of the measuring filters***

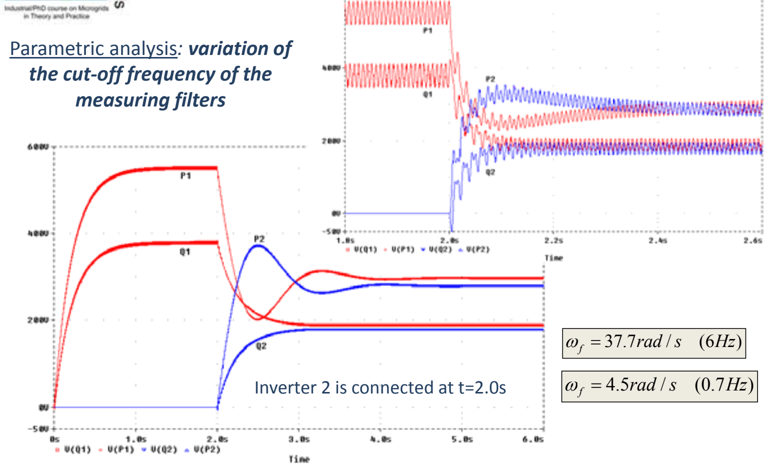
Root locus

$0.75 < \omega_f < 75.4 rad/s$



4.4. Small-Signal Analysis of a Stand-alone System

Parametric analysis*: variation of the cut-off frequency of the measuring filters*



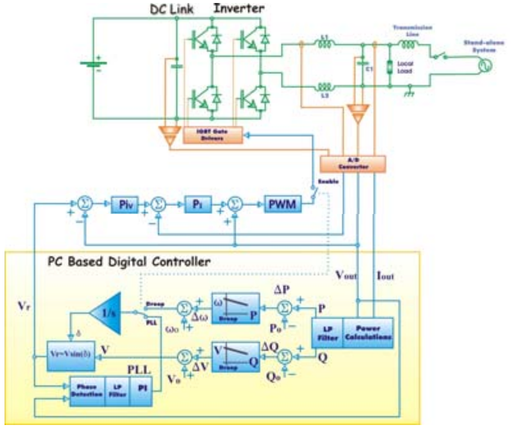
Inverter 2 is connected at t=2.0s

$$\omega_f = 37.7 rad/s \quad (6Hz)$$

$$\omega_f = 4.5 rad/s \quad (0.7Hz)$$

4.4. Small-Signal Analysis of a Stand-alone System

Experimental Results - Stand-alone System composed by 2 units



Scheme for each inverter

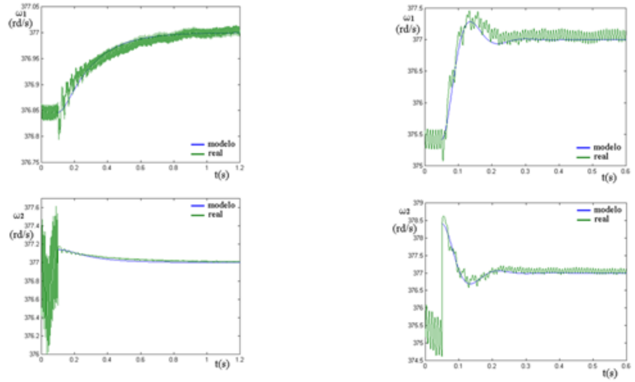
4.4. Small-Signal Analysis of a Stand-alone System

Experimental Results - Stand-alone System composed by 2 units

[Coelho et al., 2002]

Inverter Frequency

Test 1 Test 2



Kp=0.0005 rad/s/W
kv=0.0005 V/VAr

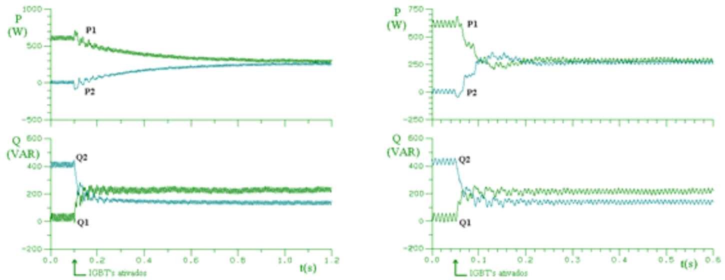
Kp=0.005 rad/s/W
kv=0.005 V/VAr

4.4. Small-Signal Analysis of a Stand-alone System

Experimental Results - Stand-alone System composed by 2 units

Active and Reactive Power

Test 1 Test 2



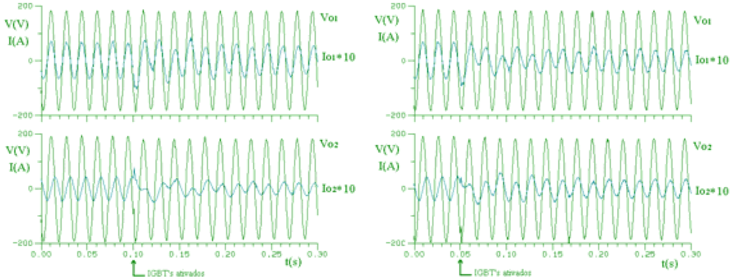
Kp=0.0005 rad/s/W
kv=0.0005 V/VAr

Kp=0.005 rad/s/W
kv=0.005 V/VAr

4.4. Small-Signal Analysis of a Stand-alone System

Experimental Results - Stand-alone System composed by 2 units

Inverter output voltage and Current



Test 1 Kp=0.0005 rad/s/W
kv=0.0005 V/VAr

Test 2 Kp=0.005 rad/s/W
kv=0.005 V/VAr

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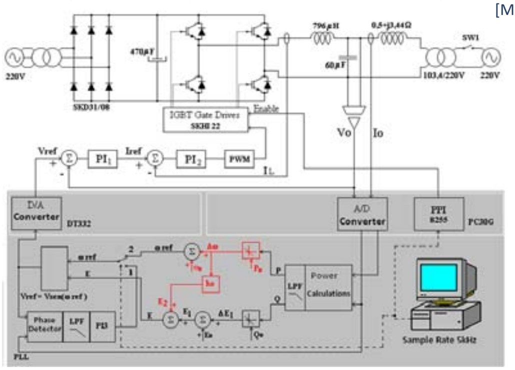
5. Advanced Strategies for Primary Control Improvements

5.1. Power System Stabilizer(PSS)

An analogous PSS subsystem is included in the droop control scheme

[Martins et al., 2002]



- It is observed in literature, some strategies to decouple the active and reactive power fluxes, but this strategy follows the opposite way.

---

5. Advanced Strategies for Primary Control Improvements

Experimental Results: Droop control method with PSS

Variable	Test 1	Test 2	Test 3	Unit
Transmission line impedance	0,5 + j3,44	0,5 + j3,44	0,5 + j3,44	Ω
Cut-off frequency of measurinf filters(ωf)	7,54	7,54	7,54	rd/s
Frequency droop gain - ωxP (K_p)	0,01	0,01	0,01	Rd/s/W
Voltage droop gain - ExQ (K_v)	0,01	0,01	0,01	V/VAR
PSS gain – feedback Δω into E_2/ (k_s)	**0**	**20**	**20**	**V/rd/s**
Control action saturation	0	0	± 5	V
Grid apparent power	500 + j0	500 + j0	500 + j0	VA
Inverter apparent power	511,7 + j80,39	511,7 + j80,39	511,7 + j80,39	VA
Grid voltage(V)	103,4	103,4	103,4	V(rms)
Inverter voltage(E)	107,11	107,11	107,11	V(rms)
Grid frequency(ω)	377	377	377	rd/s
Phase difference: inverter-grid (Δδ)	0,1558	0,1558	0,1558	rd

[Martins et al., 2002]

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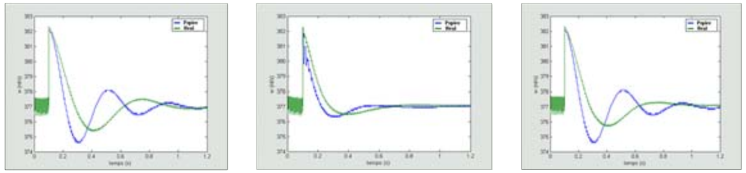
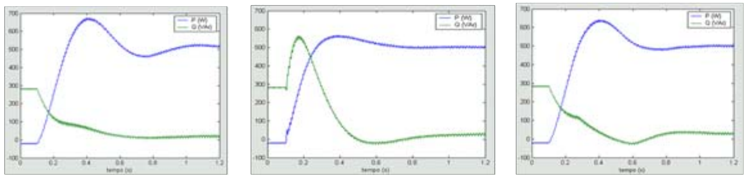
5. Advanced Strategies for Primary Control Improvements

Experimental Results: Droop control method with PSS [Martins et al., 2002]

Test 1 **Test 2** **Test 3**



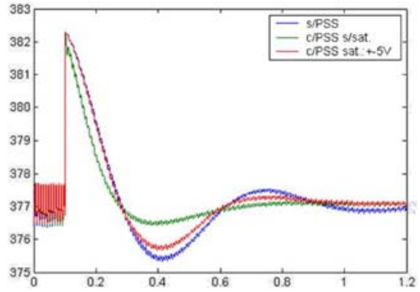
Inverter Frequency **(simulation and experimental)**



Active and Reactive Power **(experimental)**

5. Advanced Strategies for Primary Control Improvements

Experimental Results: Droop control method with PSS



Inverter Frequency

PSS effect on system dynamics

- The analogous PSS increases the system damping, but it result in a collateral effect on the reactive power;
- The voltage limiter reduces the efficiency of the PSS controller.
- Considering that the simplified PSS used here does not incorporate the washout function, neither the phase lead function, newer analysis are required.

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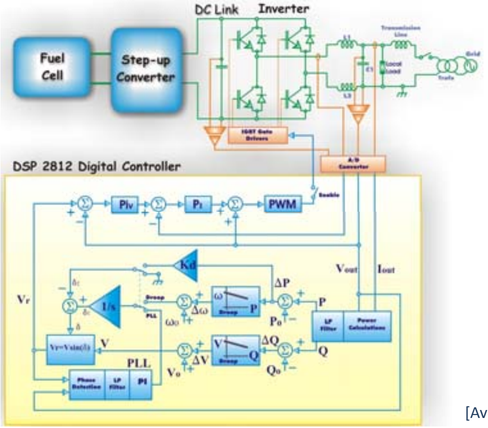
5. Advanced Strategies for Primary Control Improvements

5.2. Phase Shift – Grid Connected Inverter

Experimental Results: Droop control method with Phase Shift



[Avelar, 2012b]

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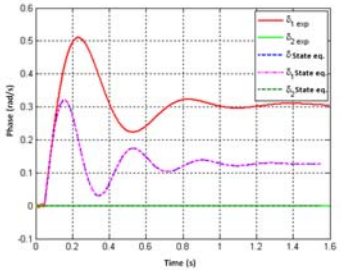
5. Advanced Strategies for Primary Control Improvements

5.2. Phase Shift – Grid Connected Inverter

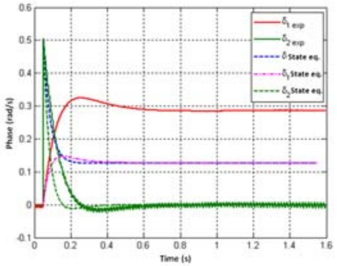
Experimental Results: Droop control method with Phase Shift **[Avelar, 2012]**

Test 1



$k_d = 0$

Test 2



$k_d = 0.001 rad / W$

Inverter Phase Components $\delta = \delta_1 + \delta_2$

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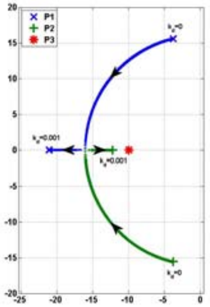
5. Advanced Strategies for Primary Control Improvements

5.2. Phase Shift – Grid Connected Inverter

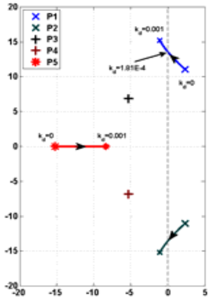
Parametric analysis: ***Phase shift loop gain variation***

1st order measuring filters



Root locus $0 < k_d < 0.001$

2nd order measuring filters



Root locus $0 < k_d < 0.001$

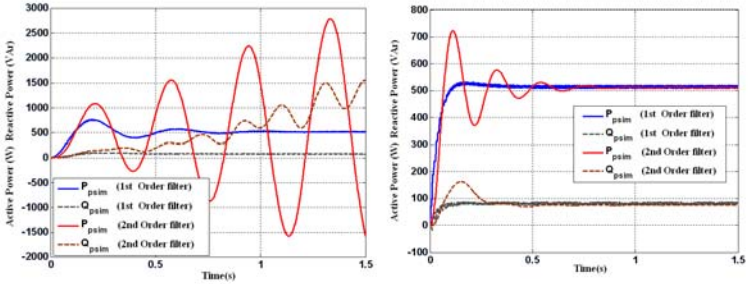
5. Advanced Strategies for Primary Control Improvements

5.2. Phase Shift – Grid Connected Inverter

Simulation Results: Droop control method with Phase Shift [Avelar, 2012]

Comparison for distinct order of the measuring filters

Active and Reactive Power



$k_d = 0$

$k_d = 0.001\,rad/W$

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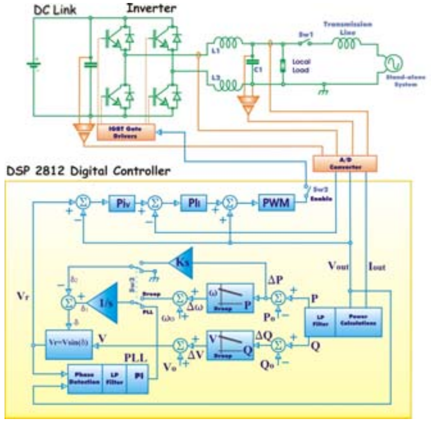
5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System



Scheme for each inverter

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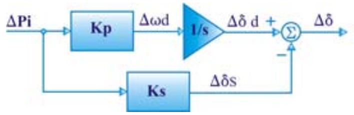
5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

Small-Signal Analysis: ***Droop control method with Phase Shift***



$$\begin{bmatrix}\Delta\dot{\omega}_i\\ \Delta\dot{e}_{di}\\ \Delta\dot{e}_{qi}\end{bmatrix} = [M_i]\begin{bmatrix}\Delta\omega_i\\ \Delta e_{di}\\ \Delta e_{qi}\end{bmatrix} + [C_{ai}]\begin{bmatrix}\Delta P_i\\ \Delta Q_i\end{bmatrix} + [C_{bi}]\begin{bmatrix}\Delta\dot{P}_i\\ \Delta\dot{Q}_i\end{bmatrix}$$

Symbolically : $[\Delta\dot{X}_i] = [M_i]\,[\Delta X_i] + [C_{ai}]\,[\Delta S_i] + [C_{bi}]\,[\Delta\dot{S}_i]$

$$[M_i] = \begin{bmatrix} -\omega_f & 0 & 0\\ \frac{nq}{m_d n_q - m_q n_d} & \frac{m_q n_d \omega_f}{m_d n_q - m_q n_d} & \frac{m_q n_q \omega_f}{m_d n_q - m_q n_d}\\ \frac{nd}{m_q n_d - m_d n_q} & \frac{m_d n_d \omega_f}{m_q n_d - m_d n_q} & \frac{k_v m_d \omega_f}{m_q n_d - m_d n_q}\end{bmatrix} \qquad [C_{ai}] = \begin{bmatrix} -k_p\,\omega_f & 0\\ 0 & \frac{k_v m_q \omega_f}{m_d n_q - m_q n_d}\\ 0 & \frac{k_v m_d \omega_f}{m_q n_d - m_d n_q}\end{bmatrix} \qquad [C_{bi}] = \begin{bmatrix} -k_s\,\omega_f & 0\\ 0 & 0\\ 0 & 0\end{bmatrix}$$

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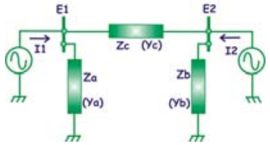
5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

Small-Signal Analysis: ***Droop control method with Phase Shift***



Symbolic nodal equation :

$$[\Delta i] = [Y_s]\quad[\Delta e]$$

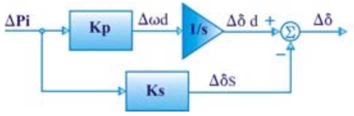
$$\begin{bmatrix}\Delta\dot{\omega}_1\\ \Delta\dot{e}_{d1}\\ \Delta\dot{e}_{q1}\\ \Delta\dot{\omega}_2\\ \Delta\dot{e}_{d2}\\ \Delta\dot{e}_{q2}\end{bmatrix} = \begin{bmatrix} M_1 & 0\\ 0 & M_2\end{bmatrix}\begin{bmatrix}\Delta\omega_1\\ \Delta e_{d1}\\ \Delta e_{q1}\\ \Delta\omega_2\\ \Delta e_{d2}\\ \Delta e_{q2}\end{bmatrix} + \begin{bmatrix} C_{a1} & 0\\ 0 & C_{a2}\end{bmatrix}\begin{bmatrix}\Delta P_1\\ \Delta Q_1\\ \Delta P_2\\ \Delta Q_2\end{bmatrix} + \begin{bmatrix} C_{b1} & 0\\ 0 & C_{b2}\end{bmatrix}\begin{bmatrix}\Delta\dot{P}_1\\ \Delta\dot{Q}_1\\ \Delta\dot{P}_2\\ \Delta\dot{Q}_2\end{bmatrix}$$

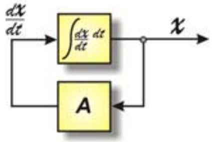
$$\begin{bmatrix}\Delta P_1\\ \Delta Q_1\\ \Delta P_2\\ \Delta Q_2\end{bmatrix} = \begin{bmatrix} i_{d1} & i_{q1} & 0 & 0\\ -i_{q1} & i_{d1} & 0 & 0\\ 0 & 0 & i_{d2} & i_{q2}\\ 0 & 0 & -i_{q2} & i_{d2}\end{bmatrix}\begin{bmatrix}\Delta e_{d1}\\ \Delta e_{q1}\\ \Delta e_{d2}\\ \Delta e_{q2}\end{bmatrix} + \begin{bmatrix} e_{d1} & e_{q1} & 0 & 0\\ e_{q1} & -e_{d1} & 0 & 0\\ 0 & 0 & e_{d2} & e_{q2}\\ 0 & 0 & e_{q2} & -e_{d2}\end{bmatrix}\begin{bmatrix}\Delta i_{d1}\\ \Delta i_{q1}\\ \Delta i_{d2}\\ \Delta i_{q2}\end{bmatrix}$$

5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

Small-Signal Analysis: ***Droop control method with Phase Shift***





Small signal model: (homogenous equation)

$$\boxed{[\Delta\dot{X}]=[A][\Delta X]}$$

$$\boxed{[X]=[X]_{eq}+[\Delta X(0)]e^{[A]t}}$$

Where:

$$[A]=\underbrace{\{[I]-[C_{bs}]([I_s]+[Es][Y_s])\,[K_e]\}^{-1}}_{\text{Phase shift}}\underbrace{\{[M_s]+[C_{as}]\,([I_s]+[Es][Y_s])\,[K_e]\}}_{\text{Conventional droop method:}}$$

[I]=Identity matrix

$$[C_{bs}]=\begin{bmatrix}C_{b1} & 0\\ 0 & C_{b2}\end{bmatrix}=\begin{bmatrix}-k_s\,\omega_f & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & -k_s\,\omega_f & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

---

5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

Small-Signal Analysis: ***Droop control method with Phase Shift***

System parameters and Equilibrium Point

Variable	Value	Unit
Local Load – Inverter 1 (Z_a)	25+j0	Ω
Local Load – Inverter 1 (Z_b)	50+j0	Ω
Line Transmission (Z_c)	0.5+j3.94	Ω
Measuring filter Cut-off frequency (ω_f)	7.54	rd/s
Frequency droop coefficient (k_p)	0.005	rad/s/W
Voltage droop coefficient (k_v)	0.005	V/VAr
Phase loop coefficient (k_s)	0.0005	rd/W
Inverter output apparent power 1	490+j5.805	VA
Inverter output apparent power 2	480+j0	VA
Inverter output voltage 1 (E_1)	127+j0	V(rms)
Inverter output voltage 2 (E_2)	127.4+j4.8	V(rms)
Nominal frequency (ω_o)	377	rd/s
Phase difference between inverter voltages	0.037664	rd

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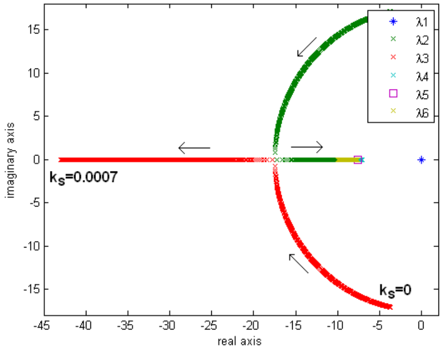
5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

Parametric analysis: ***Phase shift loop gain variation***

Root locus



$$\boxed{0<k_s<0.0007}$$

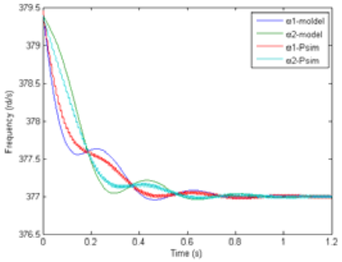
---

5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

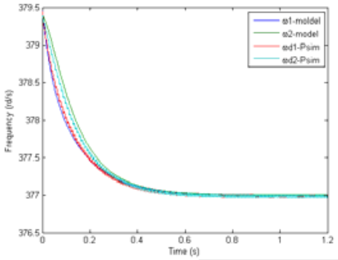
Simulation Results: Droop control method with Phase Shift

Simulation 1



$$\boxed{k_s=0}$$

Simulation 2



$$\boxed{k_s=0.0005\,rad/W}$$

$$\omega_i=\omega_{di}+\frac{d\delta_{si}}{dt}$$

Inverter frequency – System starting

5. Advanced Strategies for Primary Control Improvements

5.3. Phase Shift – Stand-alone System

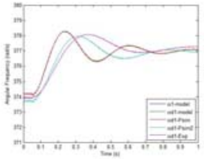
Simulation and Experimental Results: Droop control method with Phase Shift

[Parreira et al., 2014]

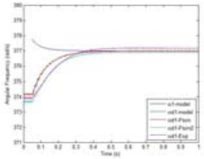
Test 1 $k_s = 0$

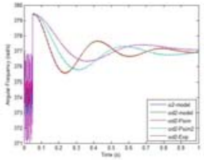
Test 2 $k_s = 0.0005\,rad/W$

Inverter frequency



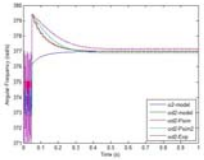
Inverter 1





Inverter 2

✓Psim2 includes the dynamic of the inverter internal controllers



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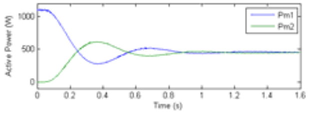
5. Advanced Strategies for Primary Control Improvements

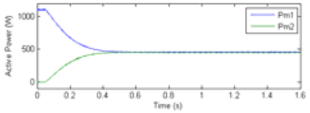
5.3. Phase Shift – Stand-alone System

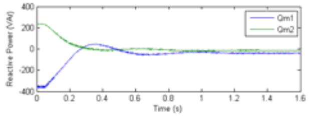
Experimental Results: Droop control method with Phase Shift

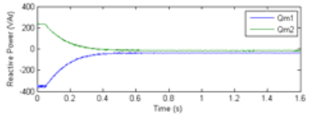
Test 1 $k_s = 0$

Test 2 $k_s = 0.0005\,rad/W$









Active and Reactive Power

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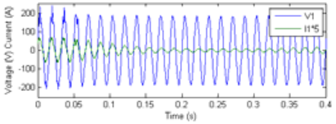
5. Advanced Strategies for Primary Control Improvements

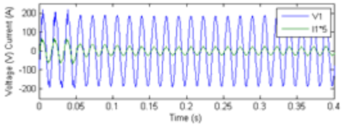
5.3. Phase Shift – Stand-alone System

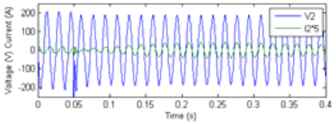
Experimental Results: Droop control method with Phase Shift

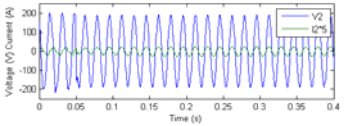
Test 1 $k_s = 0$

Test 2 $k_s = 0.0005\,rad/W$









Inverter output voltage and Current

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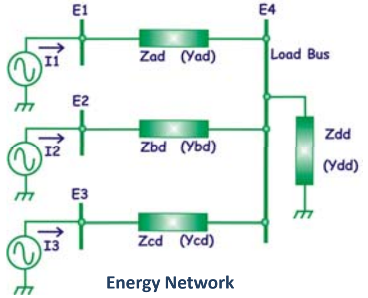
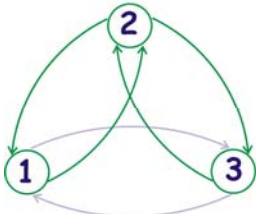
6. Small Signal Analysis for Primary and Secondary Control

Plant [Coelho et al., 2016]



Energy Network



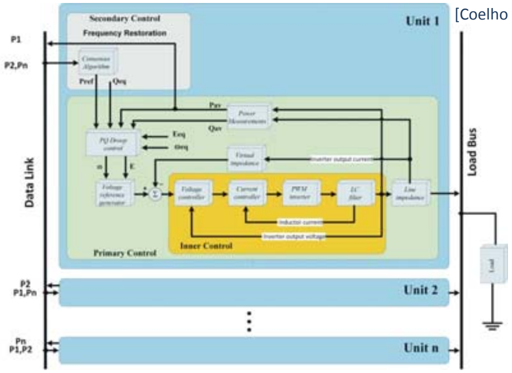
Data Network
not strongly connected
directed network

- This study is related to a microgrid composed of three inverters and a single load bus;
- The primary control is performed by the conventional droop control method;
- The secondary control integrates a consensus algorithm and a data network to provide the frequency restoration;
- The data network can be described by a directed graph, where each vertex represents an inverter and the edges represent the communication link, which it is supposed to present a constant time-delay.

6. Small Signal Analysis for Primary and Secondary Control

Microgrid scheme

[Coelho et al., 2016]



- **Primary Control** – Conventional droop control method with virtual impedance included;
- **Secondary Control** – Decentralized implementation using a consensus algorithm. A data link described by a not strongly connected directed graph is used, which presents a communication time delay. Only the frequency restoration function is considered in this study.
- **Tertiary Control** – It is not considered in this study – stand-alone operation.

---

6. Small Signal Analysis for Primary and Secondary Control

Small-Signal Model - Main equations

states

states

$$\begin{bmatrix}\Delta\dot\omega_1\\ \Delta\dot e_{d1}\\ \Delta\dot e_{q1}\\ \Delta\dot\omega_2\\ \Delta\dot e_{d2}\\ \Delta\dot e_{q2}\\ \Delta\dot\omega_3\\ \Delta\dot e_{d3}\\ \Delta\dot e_{q3}\end{bmatrix} = \begin{bmatrix}M_1&&\\&M_2&\\&&M_3\end{bmatrix}\begin{bmatrix}\Delta\omega_1\\ \Delta e_{d1}\\ \Delta e_{q1}\\ \Delta\omega_2\\ \Delta e_{d2}\\ \Delta e_{q2}\\ \Delta\omega_3\\ \Delta e_{d3}\\ \Delta e_{q3}\end{bmatrix} + \begin{bmatrix}B_{s1}&&\\&B_{s2}&\\&&B_{s3}\end{bmatrix}\begin{bmatrix}\Delta p_1\\ \Delta q_1\\ \Delta p_2\\ \Delta q_2\\ \Delta p_3\\ \Delta q_3\end{bmatrix} + \begin{bmatrix}B_{r1}&&\\&B_{r2}&\\&&B_{r3}\end{bmatrix}\begin{bmatrix}\Delta P_{ref1}\\ \Delta P_{ref2}\\ \Delta P_{ref3}\end{bmatrix} + \begin{bmatrix}B_{d1}&&\\&B_{d2}&\\&&B_{d3}\end{bmatrix}\begin{bmatrix}\Delta\dot P_{ref1}\\ \Delta\dot P_{ref2}\\ \Delta\dot P_{ref3}\end{bmatrix}$$

Droop control equation

$$\begin{bmatrix}\Delta p_1\\ \Delta q_1\\ \Delta p_2\\ \Delta q_2\\ \Delta p_3\\ \Delta q_3\end{bmatrix} = \begin{bmatrix}i_{d1}&i_{q1}&0&0&0&0\\ i_{q1}&-i_{d1}&0&0&0&0\\ 0&0&i_{d2}&i_{q2}&0&0\\ 0&0&i_{q2}&-i_{d2}&0&0\\ 0&0&0&0&i_{d3}&i_{q3}\\ 0&0&0&0&i_{q3}&-i_{d3}\end{bmatrix}\begin{bmatrix}\Delta e_{d1}\\ \Delta e_{q1}\\ \Delta e_{d2}\\ \Delta e_{q2}\\ \Delta e_{d3}\\ \Delta e_{q3}\end{bmatrix} + \begin{bmatrix}e_{d1}&e_{q1}&0&0&0&0\\ -e_{q1}&e_{d1}&0&0&0&0\\ 0&0&e_{d2}&e_{q2}&0&0\\ 0&0&-e_{q2}&e_{d2}&0&0\\ 0&0&0&0&e_{d3}&e_{q3}\\ 0&0&0&0&-e_{q3}&e_{d3}\end{bmatrix}\begin{bmatrix}\Delta i_{d1}\\ \Delta i_{q1}\\ \Delta i_{d2}\\ \Delta i_{q2}\\ \Delta i_{d3}\\ \Delta i_{q3}\end{bmatrix}$$

Power calculation

$$\begin{bmatrix}i_{d1}\\ i_{q1}\\ i_{d2}\\ i_{q2}\\ i_{d3}\\ i_{q3}\end{bmatrix} = \begin{bmatrix}G_{11}&-B_{11}&G_{12}&-B_{12}&G_{13}&-B_{13}\\ B_{11}&G_{11}&B_{12}&G_{12}&B_{13}&G_{13}\\ G_{21}&-B_{21}&G_{22}&-B_{22}&G_{23}&-B_{23}\\ B_{21}&G_{21}&B_{22}&G_{22}&B_{23}&G_{23}\\ G_{31}&-B_{31}&G_{32}&-B_{32}&G_{33}&-B_{33}\\ B_{31}&G_{31}&B_{32}&G_{32}&B_{33}&G_{33}\end{bmatrix}\begin{bmatrix}e_{d1}\\ e_{q1}\\ e_{d2}\\ e_{q2}\\ e_{d3}\\ e_{q3}\end{bmatrix}$$

It implies connections between distinct nodes!

Nodal admittance equation

---

6. Small Signal Analysis for Primary and Secondary Control

Small-Signal Model - Main equations - (continuation)

states

states

$$\begin{bmatrix}\Delta\dot\omega_1\\ \Delta\dot e_{d1}\\ \Delta\dot e_{q1}\\ \Delta\dot\omega_2\\ \Delta\dot e_{d2}\\ \Delta\dot e_{q2}\\ \Delta\dot\omega_3\\ \Delta\dot e_{d3}\\ \Delta\dot e_{q3}\end{bmatrix} = \begin{bmatrix}M_1&&\\&M_2&\\&&M_3\end{bmatrix}\begin{bmatrix}\Delta\omega_1\\ \Delta e_{d1}\\ \Delta e_{q1}\\ \Delta\omega_2\\ \Delta e_{d2}\\ \Delta e_{q2}\\ \Delta\omega_3\\ \Delta e_{d3}\\ \Delta e_{q3}\end{bmatrix} + \begin{bmatrix}B_{s1}&&\\&B_{s2}&\\&&B_{s3}\end{bmatrix}\begin{bmatrix}\Delta p_1\\ \Delta q_1\\ \Delta p_2\\ \Delta q_2\\ \Delta p_3\\ \Delta q_3\end{bmatrix} + \begin{bmatrix}B_{r1}&&\\&B_{r2}&\\&&B_{r3}\end{bmatrix}\begin{bmatrix}\Delta P_{ref1}\\ \Delta P_{ref2}\\ \Delta P_{ref3}\end{bmatrix} + \begin{bmatrix}B_{d1}&&\\&B_{d2}&\\&&B_{d3}\end{bmatrix}\begin{bmatrix}\Delta\dot P_{ref1}\\ \Delta\dot P_{ref2}\\ \Delta\dot P_{ref3}\end{bmatrix}$$

Droop control equation

Degree matrix states **Adjacency matrix** states

$$\begin{bmatrix}\Delta\dot P_{ref1}\\ \Delta\dot P_{ref2}\\ \Delta\dot P_{ref3}\end{bmatrix} = -\begin{bmatrix}k_{pr1}&0&0\\ 0&k_{pr2}&0\\ 0&0&k_{pr3}\end{bmatrix}\begin{bmatrix}1&0&0\\ 0&2&0\\ 0&0&1\end{bmatrix}\begin{bmatrix}\Delta P_{ref1}\\ \Delta P_{ref2}\\ \Delta P_{ref3}\end{bmatrix} + \begin{bmatrix}k_{pr1}&0&0\\ 0&k_{pr2}&0\\ 0&0&k_{pr3}\end{bmatrix}\begin{bmatrix}0&1&0\\ 1&0&1\\ 0&1&0\end{bmatrix}\begin{bmatrix}\Delta P_{av1}\\ \Delta P_{av2}\\ \Delta P_{av3}\end{bmatrix}$$

It implies connections between distinct nodes!

Distributed control law

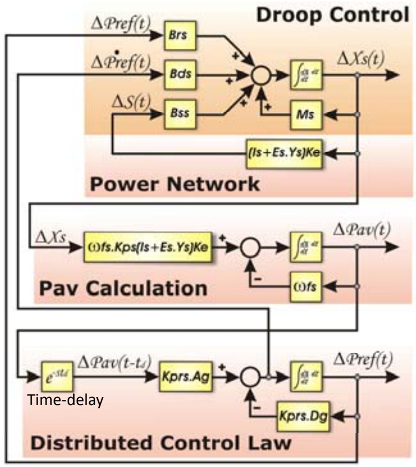
states

$$\begin{bmatrix}\Delta\dot P_{av1}\\ \Delta\dot P_{av2}\\ \Delta\dot P_{av3}\end{bmatrix} = -\begin{bmatrix}\omega_{f1}&0&0\\ 0&\omega_{f2}&0\\ 0&0&\omega_{f3}\end{bmatrix}\begin{bmatrix}\Delta P_{av1}\\ \Delta P_{av2}\\ \Delta P_{av3}\end{bmatrix} + \begin{bmatrix}\omega_{f1}&0&0\\ 0&\omega_{f2}&0\\ 0&0&\omega_{f3}\end{bmatrix}\begin{bmatrix}\Delta p_1\\ \Delta p_2\\ \Delta p_3\end{bmatrix}$$

Average power calculation

---

6. Small Signal Analysis for Primary and Secondary Control



Time-delay

$$\Delta X_s(t) = \begin{cases}\Delta\omega_1(t)\\ \Delta e_{d1}(t)\\ \Delta e_{q1}(t)\\ \Delta\omega_2(t)\\ \Delta e_{d2}(t)\\ \Delta e_{q2}(t)\\ \Delta\omega_3(t)\\ \Delta e_{d3}(t)\\ \Delta e_{q3}(t)\end{cases}$$

$$\Delta P_{av}(t) = \begin{cases}\Delta P_{av1}(t)\\ \Delta P_{av2}(t)\\ \Delta P_{av3}(t)\end{cases}$$

$$\Delta P_{ref}(t) = \begin{cases}\Delta P_{ref1}(t)\\ \Delta P_{ref2}(t)\\ \Delta P_{ref3}(t)\end{cases}$$

6. Small Signal Analysis for Primary and Secondary Control

Small-Signal Model – Delay Differential Equation (DDE)

[Coelho et al., 2016]

$$
\begin{bmatrix}\Delta\dot{\omega}_1(t)\\ \Delta\dot{e}_{d1}(t)\\ \Delta\dot{e}_{q1}(t)\\ \Delta\dot{\omega}_2(t)\\ \Delta\dot{e}_{d2}(t)\\ \Delta\dot{e}_{q2}(t)\\ \Delta\dot{\omega}_3(t)\\ \Delta\dot{e}_{d3}(t)\\ \Delta\dot{e}_{q3}(t)\\ \Delta\dot{P}_{av1}(t)\\ \Delta\dot{P}_{av2}(t)\\ \Delta\dot{P}_{av3}(t)\\ \Delta\dot{P}_{ref1}(t)\\ \Delta\dot{P}_{ref2}(t)\\ \Delta\dot{P}_{ref3}(t)\end{bmatrix}
=
\left[\begin{array}{c|c|c}
\begin{matrix}M_s\\ +B_{ss}(I_s+E_sY_s)k_e\end{matrix} & \begin{matrix}0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\end{matrix} & \begin{matrix}B_{rs}\\ -B_{ds}k_{prs}D_g\end{matrix}\\ \hline
\omega_{fs}k_{ps}(I_s+E_sY_s)k_e & -\omega_{fs} & \begin{matrix}0&0&0\\0&0&0\\0&0&0\end{matrix}\\ \hline
\begin{matrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{matrix} & \begin{matrix}0&0&0\\0&0&0\\0&0&0\end{matrix} & -k_{prs}D_g
\end{array}\right]
\begin{bmatrix}\Delta\omega_1(t)\\ \Delta e_{d1}(t)\\ \Delta e_{q1}(t)\\ \Delta\omega_2(t)\\ \Delta e_{d2}(t)\\ \Delta e_{q2}(t)\\ \Delta\omega_3(t)\\ \Delta e_{d3}(t)\\ \Delta e_{q3}(t)\\ \Delta P_{av1}(t)\\ \Delta P_{av2}(t)\\ \Delta P_{av3}(t)\\ \Delta P_{ref1}(t)\\ \Delta P_{ref2}(t)\\ \Delta P_{ref3}(t)\end{bmatrix}
$$

$$
+\left[\begin{array}{c|c|c}
\begin{matrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{matrix} & B_{ds}k_{prs}A_g & \begin{matrix}0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\\0&0&0\end{matrix}\\ \hline
\begin{matrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{matrix} & \begin{matrix}0&0&0\\0&0&0\\0&0&0\end{matrix} & \begin{matrix}0&0&0\\0&0&0\\0&0&0\end{matrix}\\ \hline
\begin{matrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\end{matrix} & k_{prs}A_g & \begin{matrix}0&0&0\\0&0&0\\0&0&0\end{matrix}
\end{array}\right]
\begin{bmatrix}\Delta\omega_1(t-t_d)\\ \Delta e_{d1}(t-t_d)\\ \Delta e_{q1}(t-t_d)\\ \Delta\omega_2(t-t_d)\\ \Delta e_{d2}(t-t_d)\\ \Delta e_{q2}(t-t_d)\\ \Delta\omega_3(t-t_d)\\ \Delta e_{d3}(t-t_d)\\ \Delta e_{q3}(t-t_d)\\ \Delta P_{av1}(t-t_d)\\ \Delta P_{av2}(t-t_d)\\ \Delta P_{av3}(t-t_d)\\ \Delta P_{ref1}(t-t_d)\\ \Delta P_{ref2}(t-t_d)\\ \Delta P_{ref3}(t-t_d)\end{bmatrix}
$$

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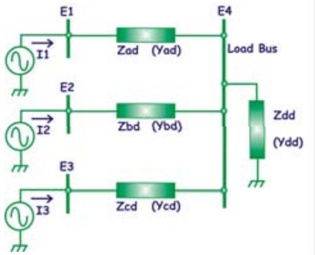
6. Small Signal Analysis for Primary and Secondary Control

Simulation and experimental results



System Parameters and Equilibrium Point

Variable	Value	Unit
Inverter LC filter		
inductor	1.8	mH
capacitor	27.0	μH
Load 1	$119 + j0$	Ω
Load 2	$119 + j0$	Ω
Line transmission - inverter 1	$0.2 + j1.131$	Ω
Line transmission - inverter 2 and 3	$0.1 + j0.566$	Ω
Measuring filter cut-off frequency ($\omega_{f1} = \omega_{f2} = \omega_{f3}$)	31.4159	rad/s
Frequency droop coefficient ($k_{p1} = k_{p2} = k_{p3}$)	0.0004	rad/s/W
Voltage droop coefficient ($k_{v1} = k_{v2} = k_{v3}$)	0.0005	V/var
Frequency restoration integral gain($k_{pr1} = k_{pr2} = k_{pr3}$)	5	W/s
Voltage PR controller		
proportional gain (k_{rv})	0.06	A/V
resonant gain (k_{rexv})	40.0	A/V/s
Current PR controller		
proportional gain (k_{ri})	10.0	V/A
resonant gain (k_{rexi})	50.0	V/A/s
Virtual Impedance		
resistance (R_v)	1.5	Ω
inductance (L_v)	4	mH
Apparent power - Inverter 1 ($P_1 + jQ_1$)	$442.5 - j9.7$	VA
Apparent power - Inverter 2 ($P_2 + jQ_2$)	$442.5 + j8.6$	VA
Apparent power - Inverter 3 ($P_2 + jQ_2$)	$442.5 + j8.6$	VA
Inverter 1 output voltage ($\vec{E}_1$)	$230.0\angle 0$	V (rms), rad
Inverter 2 output voltage($\vec{E}_2$)	$229.99\angle -0.0018$	V (rms), rad
Inverter 3 output voltage($\vec{E}_3$)	$229.99\angle -0.0018$	V (rms), rad
Nominal frequency (ω)	314.159	rad/s
Switching frequency	10	kHz

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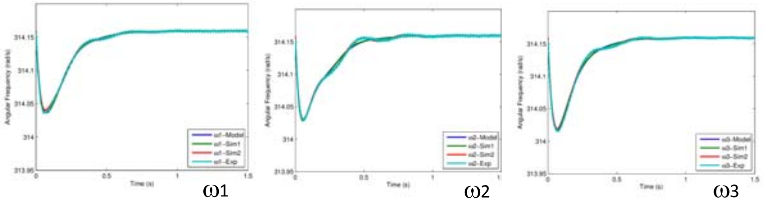
6. Small Signal Analysis for Primary and Secondary Control

Small-Signal model validation by simulation and experimental results

Frequency restoration after a load step-up – Time delay=20ms [Coelho et al., 2016]



ω1 ω2 ω3

Graph curves:

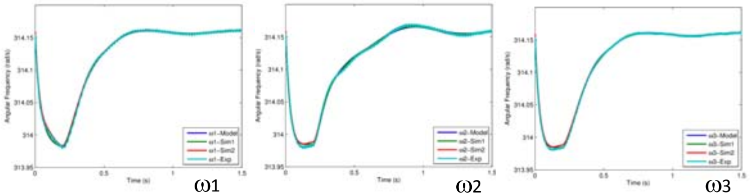
- Model → Small-signal model (solution of the DDE);
- Sim1 → Simulation considering ideal inverter, the PR internal controllers are neglected as well the virtual impedances;
- Sim2 → The internal PR controllers and the virtual impedances are considered. The PWM switching is neglected.
- Exp → Experimental result.

---

6. Small Signal Analysis for Primary and Secondary Control

Small-Signal model validation by simulation and experimental results

Frequency restoration after a load step-up – Time delay=200ms [Coelho et al., 2016]



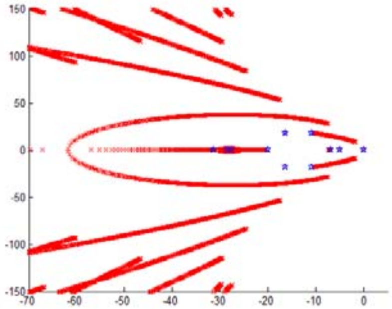
ω1 ω2 ω3

Graph curves:

- Model → Small-signal model (solution of the DDE);
- Sim1 → Simulation considering ideal inverter, the PR internal controllers are neglected as well the virtual impedances;
- Sim2 → The internal PR controllers and the virtual impedances are considered. The PWM switching is neglected.
- Exp → Experimental result.

6. Small Signal Analysis for Primary and Secondary Control

Root locus for 0 < td 200ms [Coelho et al., 2016]



DDE:
$$\begin{cases} \Delta X(t) = A\,\Delta X(t) + \dot{A}_d\,\Delta X(t-t_d); & t > 0 \\ \Delta X(0) = \emptyset(t); & t \in [-t_d, 0] \end{cases}$$

Characteristic equation: $det(-sI + A + A_d e^{-st_d})$

Obs.: The blue stars imply the eigenvalues for td=0

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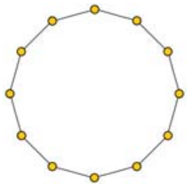
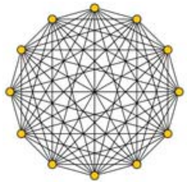
6. Small Signal Analysis for Primary and Secondary Control

Extension of the model for a twelve-inverter system



Ring data network



Regular data network

TWELVE-INVERTER SYSTEM PARAMETERS

Variable	Value	Unit
Line transmission - inverter 1	$0.2 + j1.131$	Ω
Line transmission - inverter 2	$0.1 + j0.566$	Ω
Line transmission - inverter 3	$0.1 + j0.314$	Ω
Line transmission - inverter 4	$0.2 + j0.942$	Ω
Line transmission - inverter 5	$0.1 + j0.471$	Ω
Line transmission - inverter 6	$0.1 + j0.283$	Ω
Line transmission - inverter 7	$0.2 + j1.037$	Ω
Line transmission - inverter 8	$0.1 + j0.628$	Ω
Line transmission - inverter 9	$0.1 + j0.377$	Ω
Line transmission - inverter 10	$0.2 + j0.785$	Ω
Line transmission - inverter 11	$0.1 + j0.503$	Ω
Line transmission - inverter 12	$0.1 + j0.298$	Ω
Load 1	$40 + j0$	Ω
Load 2	$40 + j0$	Ω

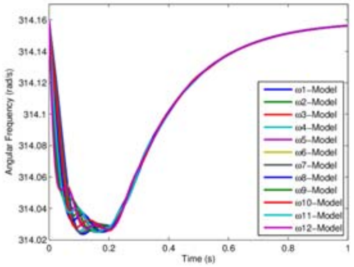
Other parameters were the same as previous results!

- It was considered a ring data network and a regular data network.
- A twelve-inverter system implies a sixty-order DDE Model.

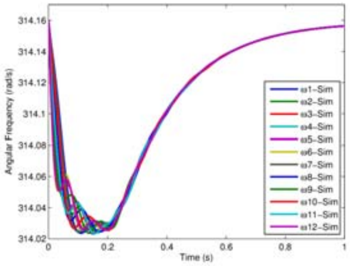
---

6. Small Signal Analysis for Primary and Secondary Control

Extension of the model for a twelve-inverter system



Twelve-inverter system frequency - Regular data network — Model Result for td = 200ms



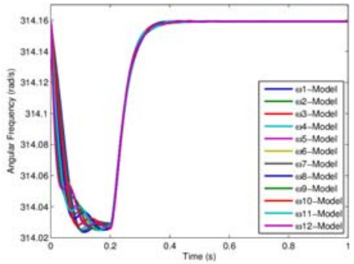
Twelve-Inverter System Frequency - Regular data network — Simulation Result for td = 200ms

- There is a good agreement between model and simulation results.
- A ring data network implies a slower convergence to the steady-state.
- It was considered a communication time-delay of 200ms.

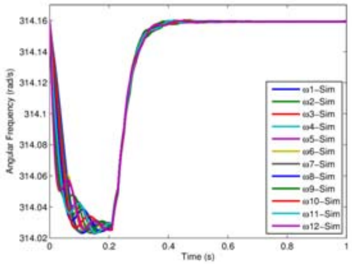
---

6. Small Signal Analysis for Primary and Secondary Control

Extension of the model for a twelve-inverter system



Twelve-inverter system frequency - Regular data network — Model Result for td = 200ms

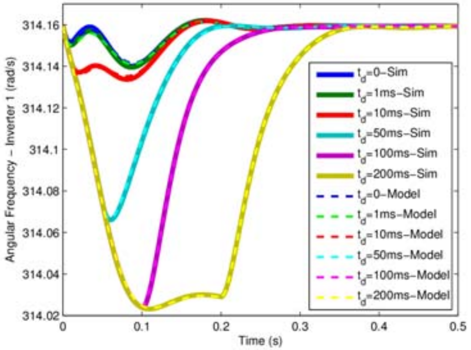


Twelve-inverter system frequency—simulation parameters: communication sampling rate: 50 Hz; packet loss probability: 0.01 and td=200ms

- A regular data network implies a faster convergence to the steady-state.
- In this case, for the simulation result, it was considered that each communication link presents a sample rate of 50 Hz, a packet loss probability of 0.01 and a time-delay of 200ms.

6. Small Signal Analysis for Primary and Secondary Control

Time delay effect determined by model and simulation



- Frequency of Inverter 1 in the Twelve-Inverter System for td = 0, 1, 10, 50, 100 and 200ms, sampling rate of 10kHz and no packet losses.
- The inverters were considered as ideal sources to obtain the simulation results.

7. Conclusions

- **The drop control method is a strategy to control the power flux sharing in a microgrid system. This strategy needs no data communication between the nodes. In some sense, one can see the droop control method as a distributed controller of a microgrid, where the communication is established by its own power transmission lines.**
- **The secondary control is responsible for the frequency and voltage restoration functions. It can be implemented in a centralized or decentralized way and it depends on communication to work. Even considering that the secondary control works in external level at a low bandwidth, the inherent time-delay of the communication system should be taken into account.**
- **The microgrid based on droop control method at the primary level is a non-linear system, thus the small-signal analysis is an important tool to preview the dynamic behavior of the microgrid systems. This tool can be applied in the primary and secondary control.**
- **In order to make the small-signal analysis simple, only the first derivative term of the Taylor series is considered, which implies that the small-signal model is accurate only in the neighborhood of the equilibrium point.**

7. Conclusions

- **Another simplification in the presented approach to build the small-signal model is the neglecting of the internal control dynamics of the inverters. The inclusion of the inverter internal dynamics increases the model order and makes the analysis more difficult. According the presented results, this simplification is reasonable when the bandwidth of the internal controllers is much higher than the bandwidth related to the primary control. This implies the necessity of a significant level of the connection impedances, which can be increased using the virtual impedances.**
- **Considering the presented approach for the frequency restoration at the secondary control level, one can see that a unique and constant time-delay in the communication links doesn't compromise the system stability.**
- **The constant time-delay can be implemented in a practical communication system by means of some techniques that make it equal to the upper bound of the total allowed delay in the system.**
- **The typical sampling rate and the packet loss observed in these communication systems do not affect the performance of the secondary control in the studied microgrid.**

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Microgrids
Industrial/PhD course on Microgrids in Theory and Practice

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Microgrids
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Thank you for your attention!

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Distributed Energy Storage Systems

Josep M. Guerrero, Prof. Aalborg University

AC Microgrids

Industrial/PhD course on Microgrids
in Theory and Practice

Distributed Energy Storage Systems

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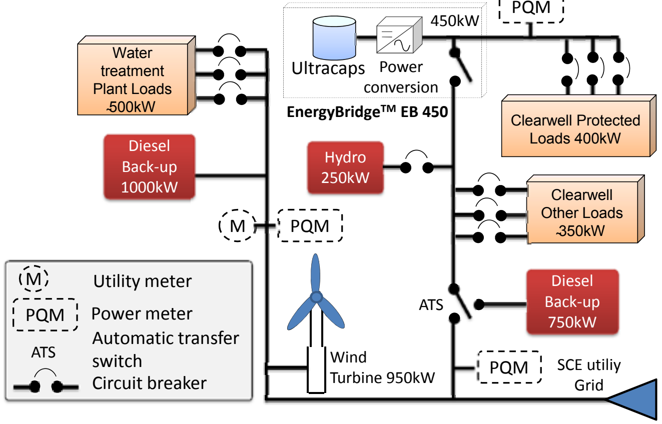
Outline

- Energy storage in island Microgrids
- Energy storage in grid-connected Microgrids. Peak shaving.
- Energy storage devices
- Batteries
- Flow Batteries
- Supercapacitors
- Superconductor Magnetics Energy Storage SMES
- Flywheels
- Compress Air Energy Storage Systems (CAES)
- Applications
- Energy-Power trade-off
- Conclusions
- References

Energy Storage Systems

Energy storage in Microgrids

Palmdale Water District Power System



PQM

450kW

Ultracaps

Power conversion

EnergyBridge^{TM} EB 450

Water treatment Plant Loads 500kW

Diesel Back-up 1000kW

Hydro 250kW

Clearwell Protected Loads 400kW

Clearwell Other Loads 350kW

M

PQM

ATS

Diesel Back-up 750kW

Wind Turbine 950kW

PQM

SCE utiliy Grid

M Utility meter

PQM Power meter

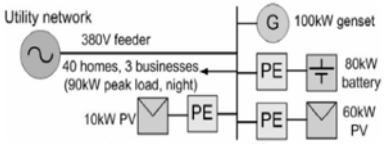
ATS Automatic transfer switch

Circuit breaker

Energy Storage Systems

XingXingXia，XinJiang Province, China (星星峡, 新疆)

Decentralized rural electrification using renewable energies



Energy Storage Systems

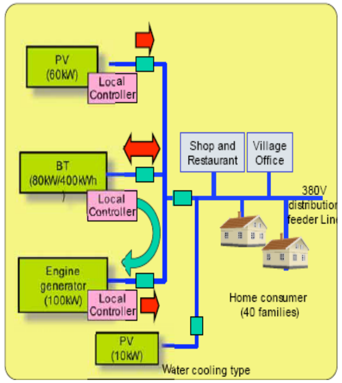
Power Balance

1. Electric Power Generation

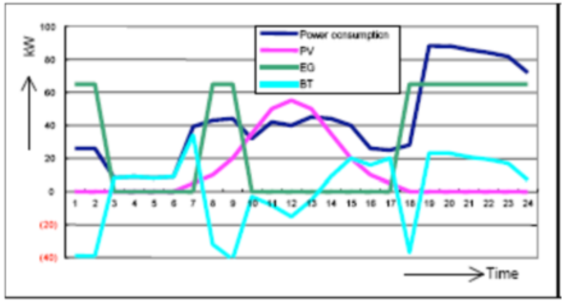
Engine Generator	**100kW**
PV	**70kW**
Batteries	**80kW (400kWh)**
	250kW

2. Peak Load 90kW (at night time)

3. Distribution feeder 380V /500m

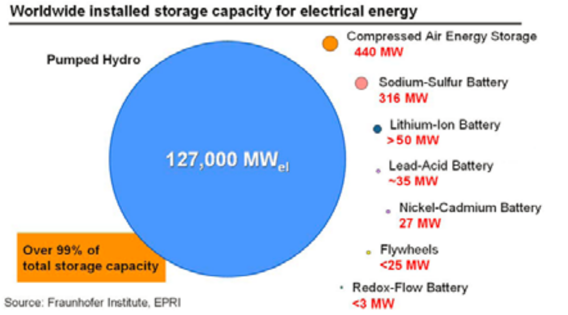


Energy Storage Systems



Load and Generation Curve

Energy Storage Systems



Source: EPRI, "Electricity Energy Storage Technology Options – A White Paper Primer on Applications, Costs, and Benefits", Dec. 2010

- despite the real need for energy storage systems within the power system, very few grid-integrated storage installations are in actual operation in EU and US today;
- this landscape is expected to change around 2012, when new energy storage systems are expected to be deployed worldwide, especially in US.

Batteries

Lead acid batteries

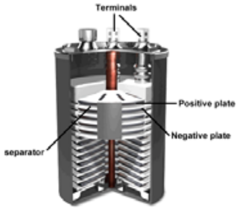
- most commonly used energy storage systems for UPS
- Continuous power 30-50 W/kg
- Deliverable energy 75-300 Wh/kg
- Typical back-up time 5-30 min
- System price: Energy 200-400 $/kWh
- System price: Power 300-600 $/kW

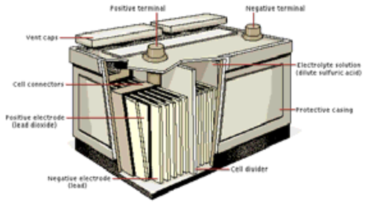
Advantages

- Proven technology
- Low cost
- Very low standby losses
- High modularity

Drawbacks

- Sensitivity to temperature
- Large volume and weight
- Limited charge/discharge cycles
- High failure rate
- Environmental impact





Source: GE

Batteries

Sodium Sulphur (NaS) Batteries

- Continuous power 150-230 W/kg
- Deliverable energy 150-240 Wh/kg
- Typical back-up time 5-30 min
- System price: Energy 300-500 $/kWh
- System price: Power 1000-3000 $/kW

Advantages

- mature battery technology
- high efficiency (80-90%)
- Relative long cycle life
  - 2500 @ 100% DOD
  - 4500 @ 90% DOD
- pulse power capability of over six times their continuous rating for 30 seconds

Drawbacks

- Only one manufacturer (NGK Insulators Ltd.)
- Operation temperature 300°C – high stand-by consumption
- Fire events
- Environmental impact

NaS batteries in grid applications

World's largest NaS battery installation – 34 MW wind-stabilization system for a 51 MW wind farm at Futumata, Japan

1.5 MW NaS battery alongside 5 MW Solar PV Array, Hokkaido Electric Power Co.

Batteries

Sodium/Nickel Chloride batteries

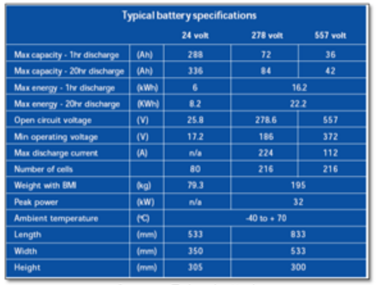
- Continuous power 150-200 W/kg,
- Deliverable energy 100-120 Wh/kg
- Typical back-up time 30min-hours
- System price: Energy 100-200 $/kWh

Advantages

- High energy density
- Insensitive to ambient temperature
- Maintenance free construction
- Long service life
- Low environmental impact
- Short charging time
- Unproblematic storage

Drawbacks

- Current cost
- Management electronic needed
- Put into operation time (>1day)
- Fast self-discharge (< 2 weeks)



Typical battery specifications

		24 volt	278 volt	557 volt
Max capacity - 1hr discharge	(Ah)	288	72	36
Max capacity - 20hr discharge	(Ah)	336	84	42
Max energy - 1hr discharge	(kWh)	6	16.2	
Max energy - 20hr discharge	(KWh)	8.2	22.2	
Open circuit voltage	(V)	25.8	278.6	557
Min operating voltage	(V)	17.2	186	372
Max discharge current	(A)	n/a	224	112
Number of cells		80	216	216
Weight with BMI	(kg)	79.3	195	
Peak power	(kW)	n/a	32	
Ambient temperature	(°C)	-40 to + 70		
Length	(mm)	533	833	
Width	(mm)	350	533	
Height	(mm)	305	300	

Source: Zebra batteries

Batteries

Lithium-ion batteries

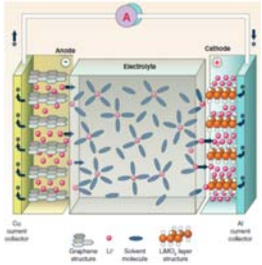
- relatively new technology
- Continuous power 150 - 315 W/kg
- Deliverable energy 75 - 200 Wh/kg
- System price: Energy 450 - 500 $/kWh

Advantages

- Very high efficiency 85-95%
- Long cycle life
- Long service life
- Low environmental impact
- Reduced self-discharge ration
- Large temperature operation range

Drawbacks

- High costs - the anticipated manufacturing scale of Li-ion batteries (approximately 35 GWh by 2015) will result in lower-costs for this technology.



Source: B. Dunn et al, "Electrical Energy Storage for the Grid: A Battery of Choices"

Expected price reduction

Lithium-Ion Batteries

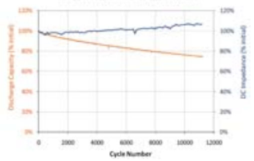
Manufacturers

SAFT	A123 Systems
BYD	Altairnano
Sanyo	Yesa
LG	Sony
GS Yuasa	Hitachi
Kokam	Panasonic

Advances in Li-ion Battery Technology

A123 Systems - *Li-ion battery based on a nanostructured $LiFePO_4$ cathode (Nanophosphate)*
- ***Increased power at low SOC and safety***
- ***round-trip efficiency*** near ***90%***;
- ***10000 – 100000 cycles*** depending on the actual Wh throughput;

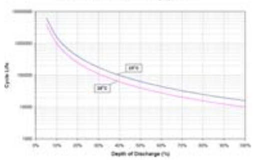
1C-1C, 100% depth of discharge (DOD) cycling



- Source: C. Vartanian, "A123 Systems' Advanced Battery Energy Storage for Renewable Integration"

Altair Nanotechnologies Inc. - *Li-ion battery based on nanotitanate anode (Battery + SuperCap)*
- ***Very High C-rate (10c)***
- ***estimated calendar life of 20 years***;
- ***more than 12000 cycles (100%DoD);***
- ***round-trip efficiency*** of about ***90%***.

Altairnano Lithium Titanate Battery Cycle Life



- Source: Altair Nanotechnologies Inc., "Applications for Advanced batteries in Microgrid Environments"

Lithium-Ion Batteries

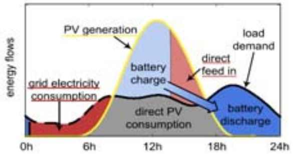
Li-ion Battery Systems – in stationary applications

32 MW energy storage system based on Li-ion batteries at Laurel Mountain Wind Farm – used for renewable integration and frequency regulation

- Source: AES Energy

Sol-Ion Project for Residential PV 2-6kWh

Source: SAFT



Flow Batteries

Flow Battery Technologies

- Vanadium-Redox (most mature)
- Polysulphide Bromide
- Zinc Bromine etc.

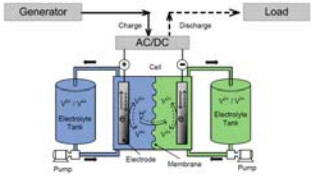
Advantages

- Power and capacity decoupled
- Fast response
- Long cycle life (up to 10000 cycles)
- Long service life (15-20 years)
- Low – medium environmental impact
- Many demonstration projects

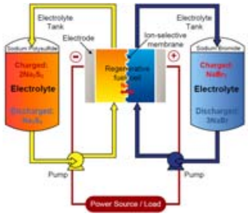
Drawbacks

- Low energy density
- High complexity - many components (pumps, control units, sensors etc.)
- High maintenance

Vanadium-Redox Flow Battery



Polysulphide Bromide Flow Battery



Supercapacitors

Supercapacitors

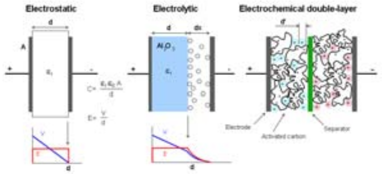
- Continuous power 500-5000 W/kg
- Deliverable energy 2.5-15 Wh/kg
- Typical back-up time 10-30 sec
- System price: Energy 300-2000 $/kWh
- System price: Power 100-300 $/kW

Advantages

- Wide operating temperature range
- Many charge/discharge cycles
- Maintenance-free
- Very high power density
- Very low standby losses
- Long service life
- Short charging time
- Low environmental impact

Drawbacks

- Cost
- Low energy density
- Voltage balancing



Source: GE

Supercapacitors

Supercapacitors

Supercapacitor, ultracapacitor, or double layer capacitor with 2700F@2.5V from Maxwell Technologies

320F to 2600F @ 2.7V.

Key features:

- Very high rates of charge and discharge.
- Little degradation over hundreds of thousands of cycles.
- Good reversibility
- Low toxicity of materials used
- High cycle efficiency (95% or more)

Disadvantages:

- The amount of energy stored is lower than batteries
- The voltage varies with the energy stored.
- Requires sophisticated electronic control and power electronics.

Superconductor Magnetics Energy Storage SMES

SMES

Superconducting Magnetic Energy Storage (SMES) with 2 MJ, 0.6 kWh capacity

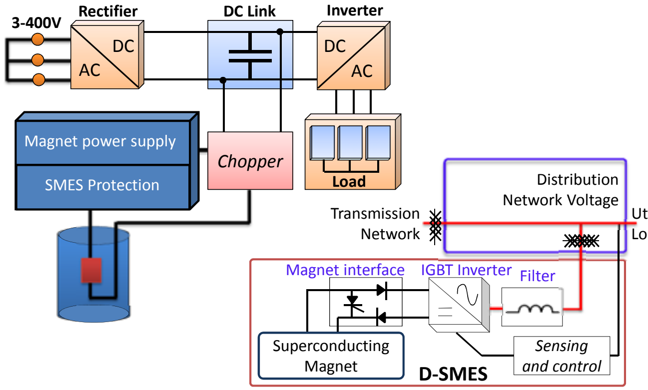
Superconductor coil formed by NbTi cooled by liquid He at 4.2 K

By courtesy of ACCEL Instruments GmbH

Superconductor Magnetics Energy Storage SMES

SMES

UPS example with SMES



Flywheels

Medium speed Flywheel: mechanical storage, wheel speed 5000-10000 rpm

- Continuous power 400-1500 W/kg
- Deliverable energy 10-30 Wh/kg
- Typical back-up time 10-30 sec
- System price: Energy 1000-5000 $/kWh
- System price: Power 250-350 $/kW

Advantages

- Wide operating temperature range
- Many charge/discharge cycles
- High power density
- Short charging time/very long service life
- Low environmental impact

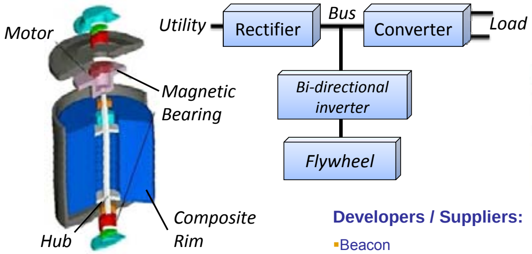
Drawbacks

- Cost
- Low energy density
- Stand-by losses
- Maintenance and Installation
- Audible Noise

Source: Beacon Power

Flywheels

Flywheel unit with 6 kWh from Beacon Power



Key features:

- little maintenance
- long life (20 years or 10,000 deep cycles)
- environmentally inert material

Developers / Suppliers:

- Beacon
- Active Power, Inc.
- AFS Trinity Power
- Piller Gmb
- Urenco Power Technologies Limited

Flywheels

High speed Flywheel: wheel speed 40000-60000 rpm

- Continuous power 400-1500 W/kg
- Deliverable energy 15-35 Wh/kg
- Typical back-up time 10-30 sec
- System price: Energy 2000-7000 $/kWh
- System price: Power 250-350 $/kW

Advantages

- Wide operating temperature range
- Many charge/discharge cycles
- High power density
- Very long service life
- Short charging time
- Low environmental impact

Drawbacks

- Cost
- Low energy density
- Maintenance

Source: Active power

Compress Air Energy Storage Systems (CAES)

Commercial CAES history:

- 1st 290 MW Hundorf, Germany 1978
- 2nd 110 MW McIntosh, Alabama 1991.
  - construction 30 months
  - cost $65M
  - comes on line within 14 minutes
- 3rd 2700 MW Norton, Ohio (in process)

- CAES in appropriate underground mines or caverns created inside salt rocks.
- It takes about 1.5 to 2 years to create such a cavern by dissolving salt.

Compress Air Energy Storage Systems (CAES)

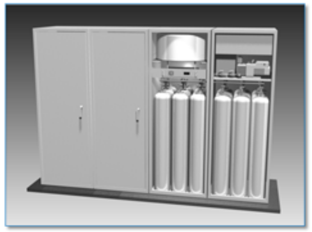
- Deliverable energy 30-60 Wh/kg
- Typical back-up time 5-30min
- System price: Energy 2-50 $/kWh
- System price: Power 400-800 $/kW

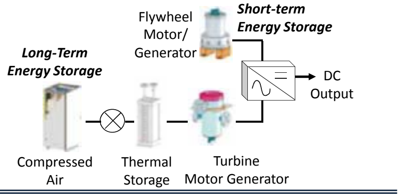
Advantages

- Wide operating temperature range
- Many charge/discharge cycles
- Very long service life (20 years)
- Low environmental impact

Drawbacks

- Current cost
- Stand-by losses
- Energy density
- Complex system





Flywheel Motor/ Generator

Short-term Energy Storage

Long-Term Energy Storage

DC Output

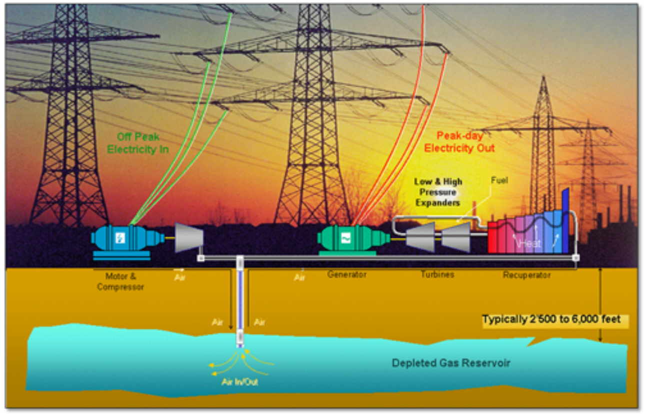
Compressed Air

Thermal Storage

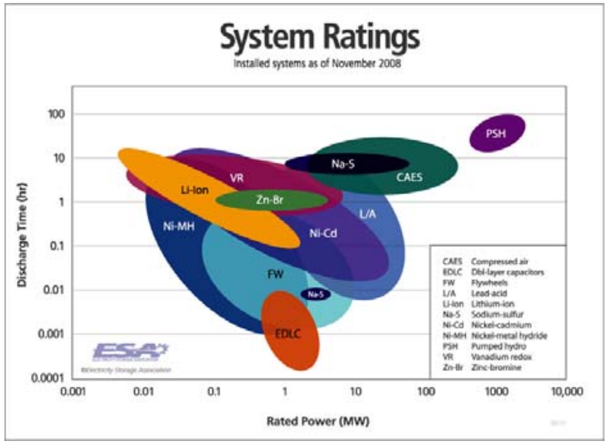
Turbine Motor Generator

Compress Air Energy Storage Systems (CAES)

Applications

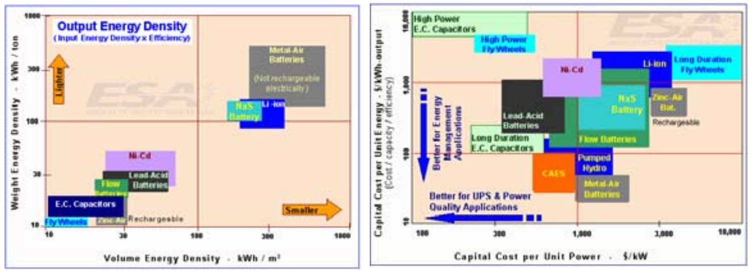


Technology Comparison



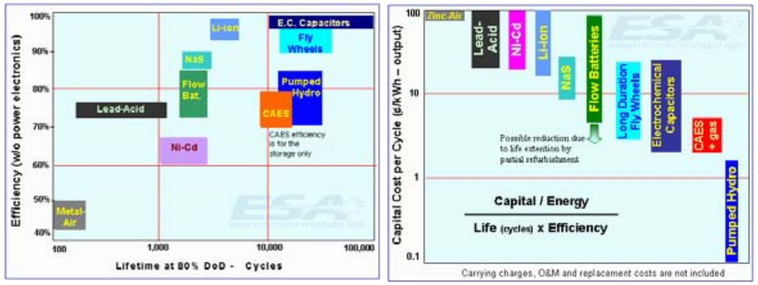
Source: http://www.electricitystorage.org

Technology Comparison



Source: http://www.electricitystorage.org

Technology Comparison



Source: http://www.electricitystorage.org

Energy Storage Systems

Technical and economical comparison of different energy storage technologies

	CAES	Flow Battery (VRB)	Lead Acid	NaS	Zebra	Lithium-ion	Super-capacitors	SMES	Flywheels
Energy density [Wh/kg]	30-60	10-30	30-50	150-240	100-120	75-200	2.5-15	0.5-5	10-30
Power density [W/kg]			75-300	150-230	150-200	150-315	500-5000	500-2000	400-1500
Service life [years]	20 - 40	10 - 15	5 – 15	10 – 15	10 – 14	5 – 20	20+	20+	15
Cycle life [cycles @ 100% DOD]		12000+	500-1000	2500	2500+	1000-10000	100000+	100000+	20000+
Discharge time	1–24 h	up to 10h	Seconds - hours	Seconds - hours	Seconds - hours	Minutes – hours	Milliseconds – 1 hour	Milliseconds – 8seconds	Milliseconds – 15minutes
Environmental impact	moderate	moderate	high	moderate		low	low	moderate	low
Capital cost [$/kW]	400-800	600-1500	300-600	1000-3000	150-300	1200-3000	100-300	200-300	250-350
Capital cost [$/kWh]	2-50	150-1000	200-400	300-500	100-200	600-2500	300-2000	1000-10000	1000-5000

Source: H. Chen et al. *Progress in electrical energy storage system: A critical review*, Progress in Natural Science 2010

Energy Storage Systems

Conclusions

- Distributed generation also requires distributed storage, operating locally as a microgrid
- Distributed storage energy systems allows:
    - Global efficiency
    - Reliability
    - UPS functionalities
    - Active power balancing
    - Flexibility in WT and PV parks, but also in domestic renewable energy application

- Today energy storage systems uses
    - Lead-Acid batteries/gensets long back-up (>30 minutes)
    - Energy storage comprise 30 to 60% of cost and space of entire power quality systems
    - Lead-Acid drawbacks: footprint/weight, sensitivity to temperature, failure rate, toxic chemicals

- The next alternative energy storage systems uses
    - Double layer capacitors and
    - medium/high speed Flywheel interesting alternative for back-up time up to 20 seconds, considering: technical maturity, performances and costs
    - Advanced batteries and hybrid compressed air systems with current performances, level of maturity and potential for cost reduction, can be used with the next UPS generation

- The use of distributed storage energy systems allows the integration of renewable energy systems but also in new energy vectors like fuels cells and hydrogen-based technologies.

Energy Storage Systems

References

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[12] M.H. Nehrir, C. Wang, and S.R. Shaw, “Fuel cells: Promising devices for distributed generation,” IEEE Power Energy Mag., vol. 4, no. 1, pp. 47–53, Jan./Feb. 2006.
[13] W. Choi, P. Enjeti, and J.W. Howze, “Fuel cell powered UPS systems: Design considerations,” in Proc. IEEE PESC’03, pp. 385–390, June 2003.
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Hierarchical Control of AC Microgrids

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Hierarchical Control of Microgrids

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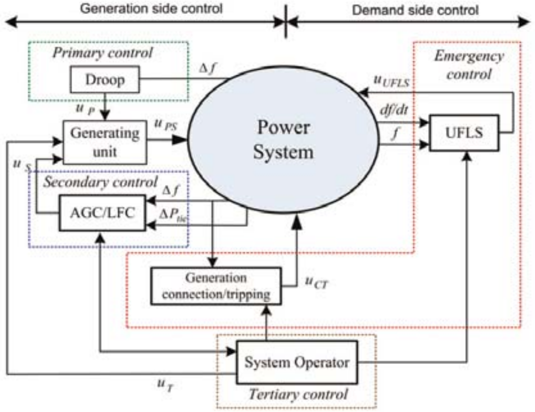
Outline

Hierarchical Control in Conventional Power Systems

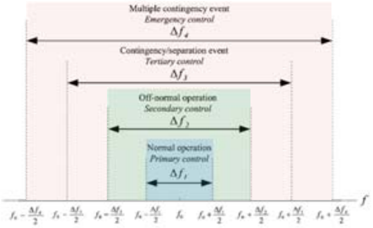
Load-Frequency control of power systems

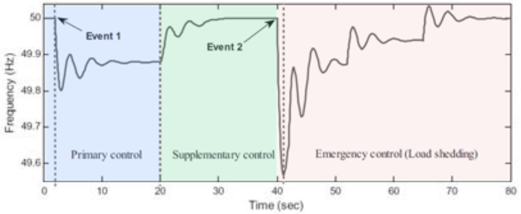


Source: H. Bevrani, *Robust Power System Frequency Control*, 2nd Edition, Springer, 2014.

Hierarchical Control in Conventional Power Systems

Frequency deviations & hierarchical controls:

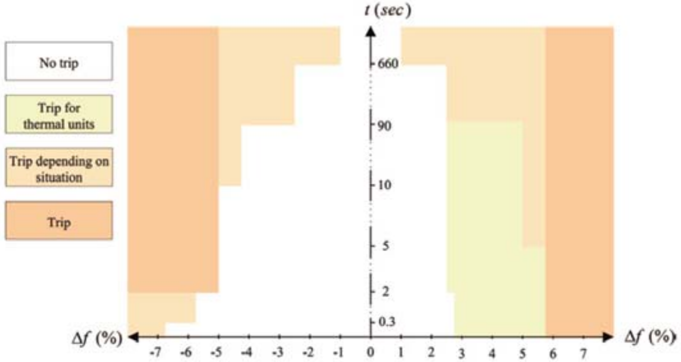




Source: H. Bevrani, *Robust Power System Frequency Control*, 2nd Edition, Springer, 2014.

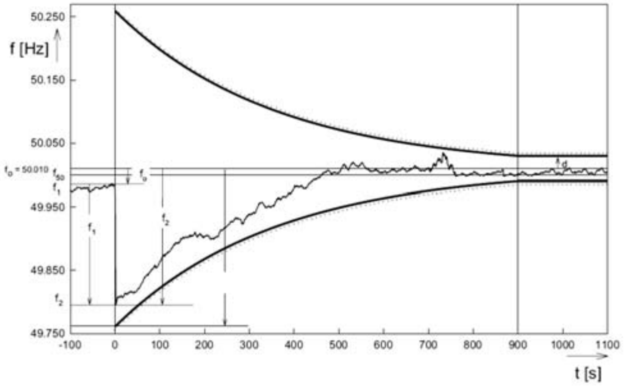
Hierarchical Control in Conventional Power Systems

Allowed frequency deviations and its duration



Source: H. Bevrani, *Robust Power System Frequency Control*, 2nd Edition, Springer, 2014.

Secondary Control in Conventional Power Systems



Source: UCTE. A1 – Appendix 1: Load-Frequency Control and Performance

Primary Control

Background in conventional power systems:

- In a synchronous generator,

energy conservation implies that

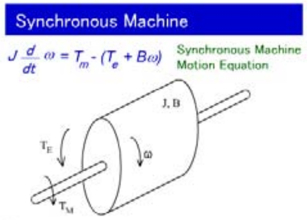
$$P_G - P_L = J\dot{\omega}$$

where

P_G is the generated real power,

P_L is the load power,

J is the system inertia, and ω is the frequency.



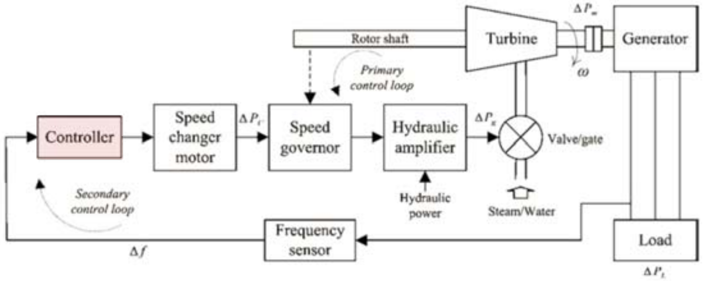
Representation of a synchronous machine

When $P_G > P_L$ the system frequency increases ($\omega > \omega_{nom}$).

When , $P_G < P_L$ the system frequency decreases ($\omega < \omega_{nom}$).

Secondary Control in Conventional Power Systems

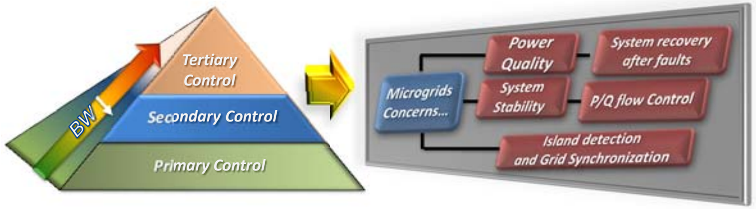
Primary and Secondary Control in Conventional Power Systesm



Source: H. Bevrani, *Robust Power System Frequency Control*, 2nd Edition, Springer, 2014.

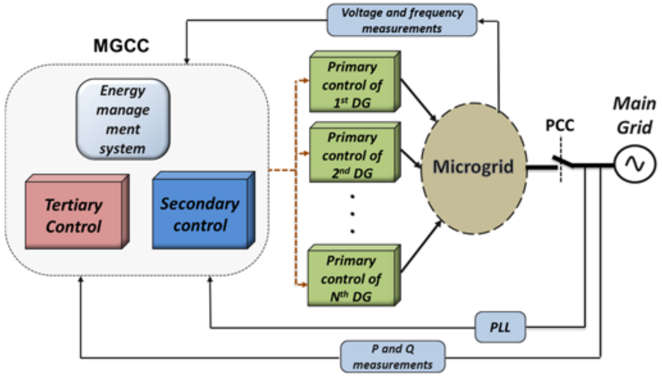
Hierarchical control in Microgrids

Hierarchical Control Principle



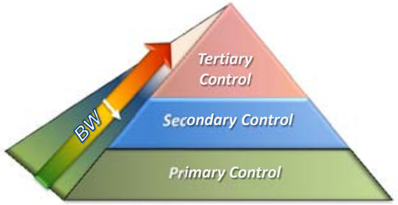
Hierarchical control in Microgrids

Conventional Hierarchical Control Arhcitecture



Hierarchical control

Hierarchical Control Tasks



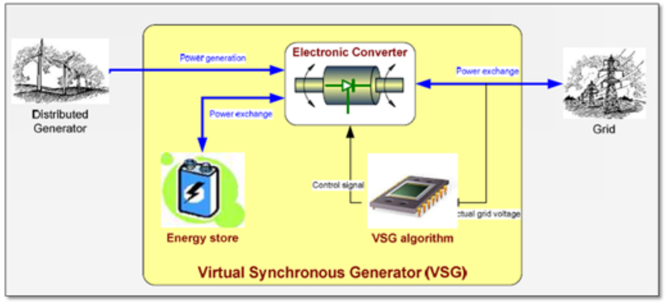
- ❑ Energy management systems
- ❑ Optimal operation in islanded mode
- ❑ power flow control in grid-connected mode

- ❑ Elimination of voltage and frequency deviations caused by primary control
- ❑ Improving power sharing
- ❑ Enhancing power quality
- ❑ Synchronization (islanded to grid-connected mode)

- ❑ Inner loops
  - ➢ Voltage and current control
- ❑ Droop control
  - ➢ Frequency and voltage stability preserving
  - ➢ Power sharing
- ❑ Virtual impedance loop
  - ➢ Fixing output impedance
  - ➢ Better power sharing

Primary Control

Virtial Synchronous Generator (VSG) Concept:



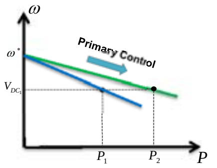
- ➢ Inertias means not only load-dependent frequency (droops), but also local storage energy system.
- ➢ The concept of Virtual Inertia (VI) or VSG has been recently used in microgrids for different control goals.

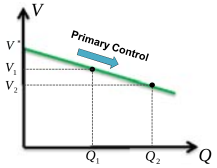
European Project VSYNC:
http://www.vsync.eu

Primary Control for Microgrids

Inverters are controlled to emulate the physics of synchronous generators.
[M. C. Chandorkar et al. '93]

The main idea of this control level is to mimic the behavior of a synchronous generator, which reduces the frequency when the active power increases.
[J. M. Guerrero et al. '11]





$$\omega = \omega^* - m_d \cdot P$$

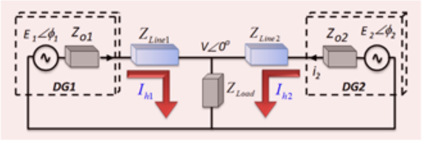
Active Power-Frequency ($P-\omega$)
Droop control

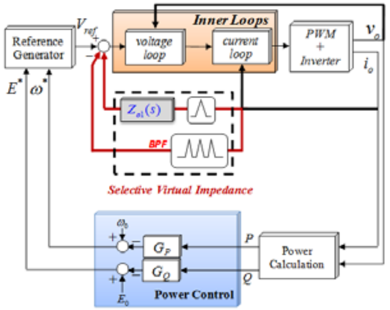
$$V = V^* - n_d \cdot Q$$

Reactive Power-Voltage ($Q-V$)
Droop control

Primary Control

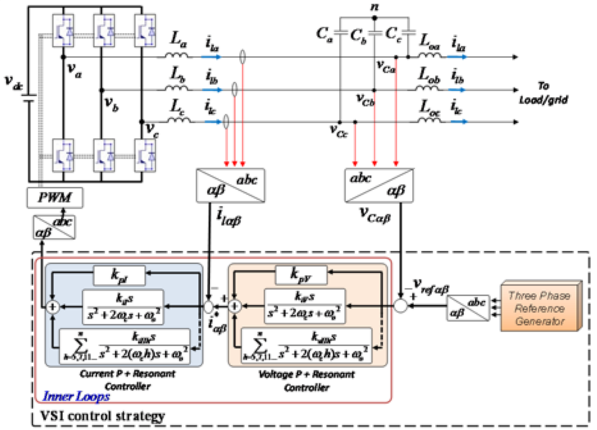
Primary control tasks and implementation





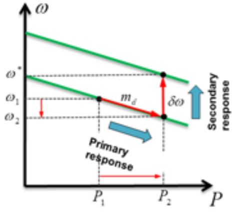
Primary Control

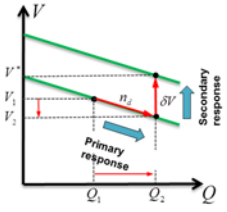
Primary control tasks and implementation- Power Quality



Secondary Control for Microgrids

- **Problem:** Steady-state frequency and voltage deviation
- **Solution:** secondary control [Chandorkar et al. '93, Lopes et al., '06, Guerrero et al., '11]





$$\omega = \omega^* - m_d \cdot P + \delta\omega$$

$$V = V^* - n_d \cdot Q + \delta V$$

In islanded microgrids, frequency and amplitude can change according to the absorption/generation of P and Q

Secondary Control Objectives

Secondary control objetives in conventional power systems:

- Minimize Area Control Error (ACE)
- Maintain frequency at the scheduled value
- Operate system with adequate security & economy
- Maintain net power interchanges
- Maintain economical power allocation
- Multiple pre-configured automatic generator control modes

Secondary Control objectives in Microgrids

Main objectives

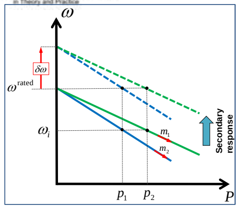
- ☐ Frequency regulation
- ☐ Voltage regulation
- ☐ power sharing

Other objectives

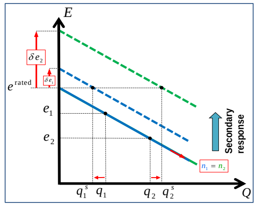
- ☐ Synchronization
- ☐ Power quality issues

Secondary Control-Main Functions

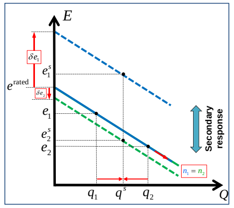
frequency restoration

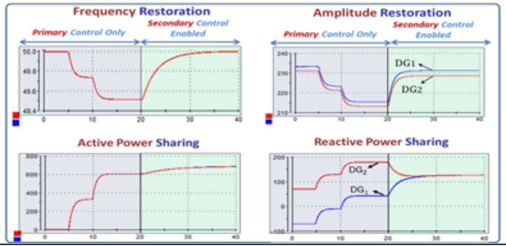


voltage restoration



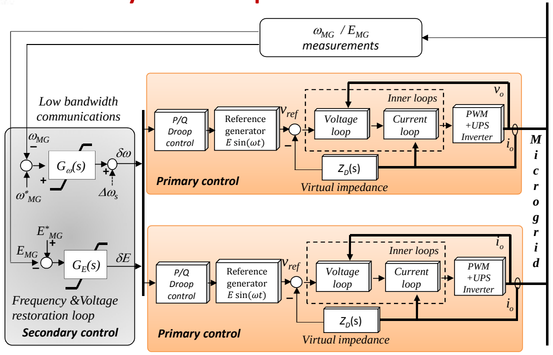
reactive power sharing





Secondary Control-Main Function

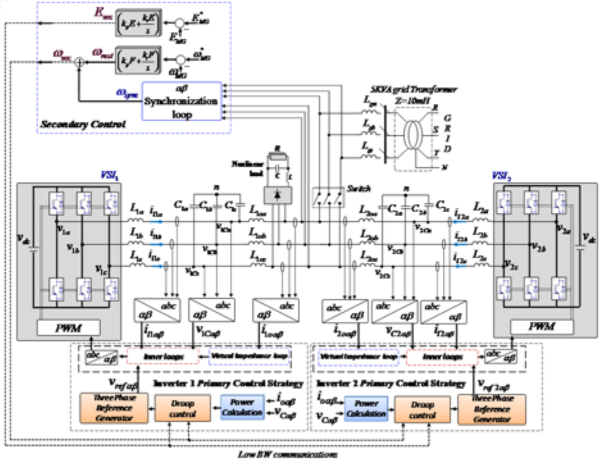
Secondary control Implementation



- ➢ Secondary control is conventionaly implemented in MGCC
- ➢ It measures frequency and voltage of the MG bus
- ➢ The control output is sent via communications to adjust the reference of the local *droops*

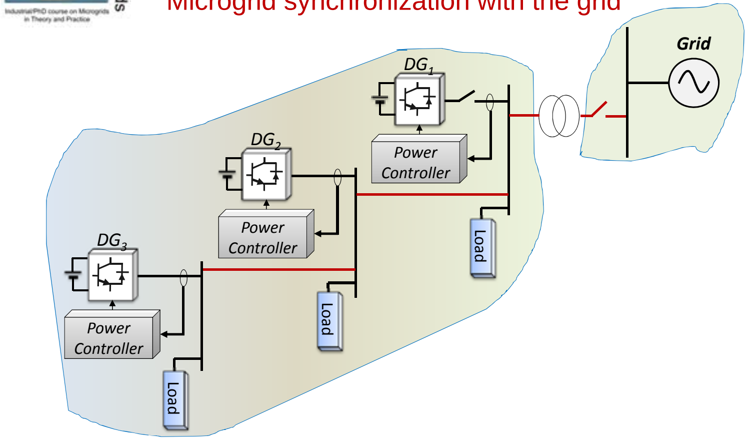
Secondary Control-Main Function

Secondary control Implementation- A Microgrid with Two VSIs

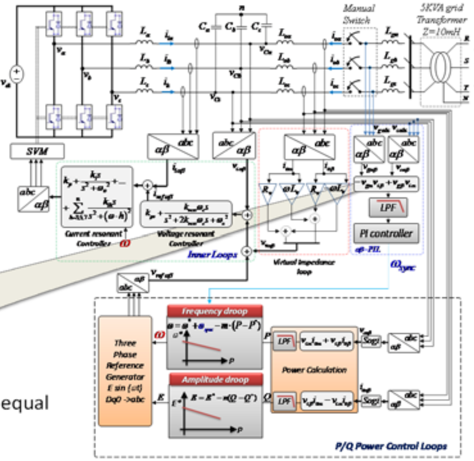


Secondary Control-Synchronization

Microgrid synchronization with the grid



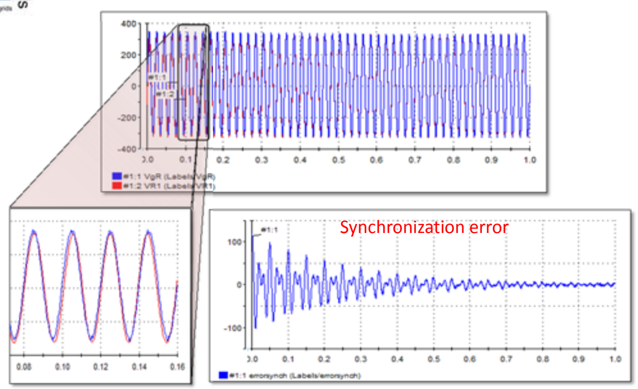
Secondary Control-Synchronization



$v_{g\beta}v_{c\alpha} - v_{g\alpha}v_{c\beta}$

Objective: make this term equal to zero.

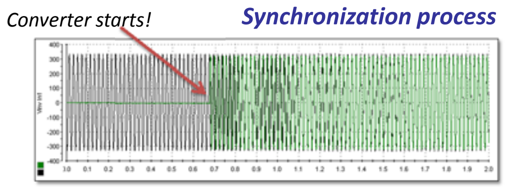
Secondary Control-Synchronization



Synchronization error

Note: Synchronization is <u>not necessary</u> to be fast: **Slow** (to avoid unstability problems) but well **accurate** (allowing seamless transition to grid-connected mode).

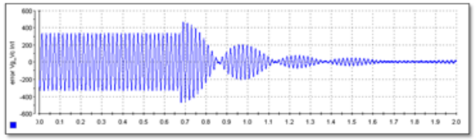
Secondary Control-Synchronization



Converter starts!

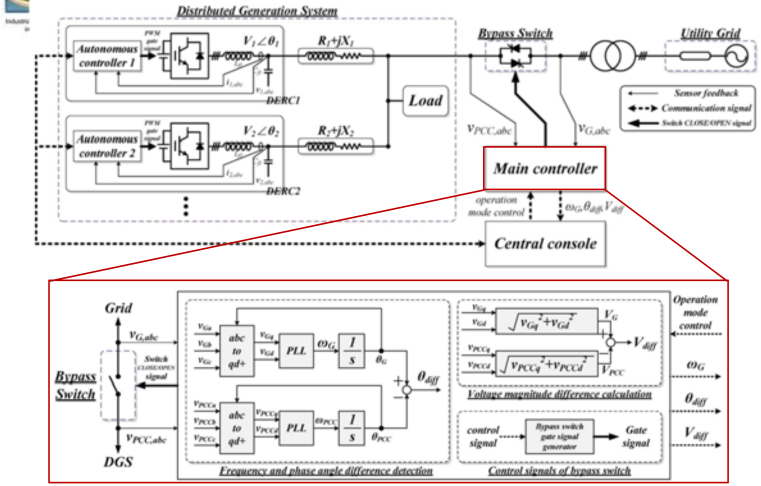
Synchronization process

Grid and converter voltages

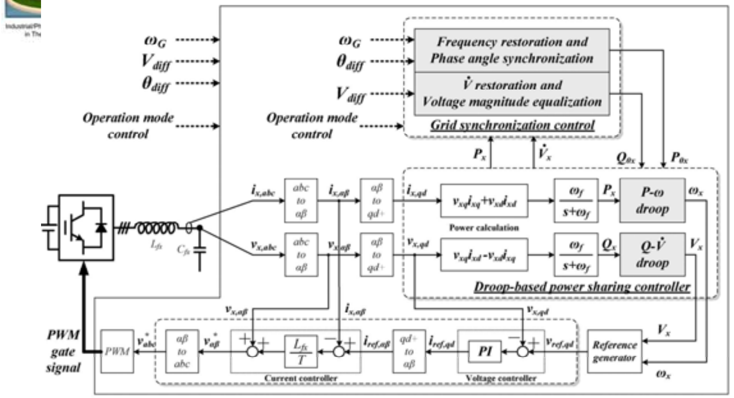


Voltage difference between grid and converter

Secondary Control-Synchronization



Secondary Control-Synchronization

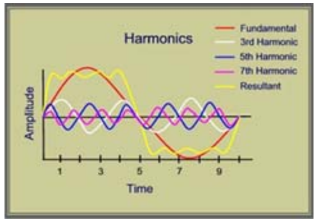


Source: C. T. Lee, R. P. Jiang and P. T. Cheng, "A Grid Synchronization Method for Droop-Controlled Distributed Energy Resource Converters," in *IEEE Transactions on Industry Applications*, vol. 49, no. 2, pp. 954-962, March-April 2013.

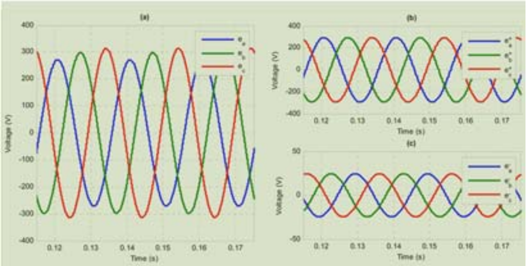
Similar works: F. Tang, J. M. Guerrero, J. C. Vasquez, D. Wu and L. Meng, "Distributed Active Synchronization Strategy for Microgrid Seamless Reconnection to the Grid Under Unbalance and Harmonic Distortion," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2757-2769, Nov. 2015.

Secondary Control-Power Quality Enhancement

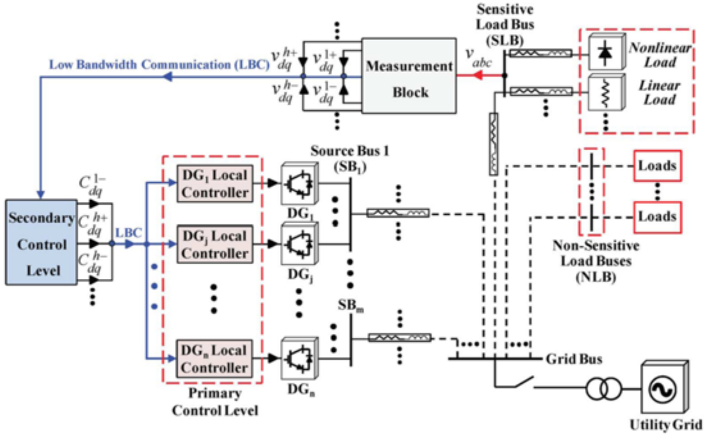
Harmonic Compensation



Unbalance Compensation

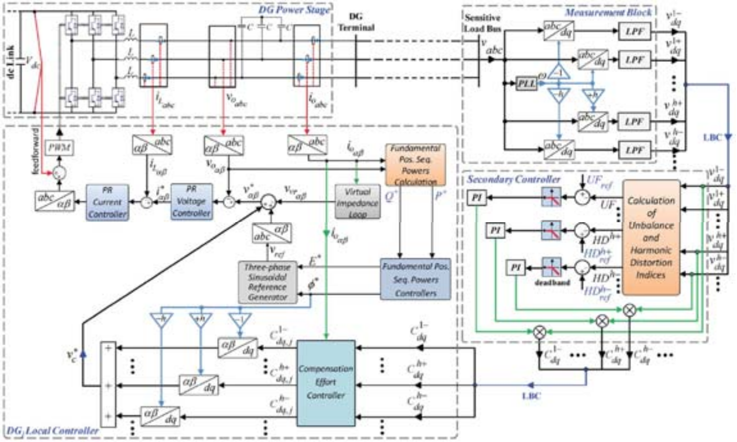


Secondary Control-Power Quality Enhancement



Source: M. Savaghebi, et al., “Secondary Control for Voltage Quality Enhancement in Microgrids,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1893–1902, Dec. 2012.

Secondary Control-Power Quality Enhancement



Source: M. Savaghebi, et al., "Secondary Control for Voltage Quality Enhancement in Microgrids," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1893–1902, Dec. 2012.

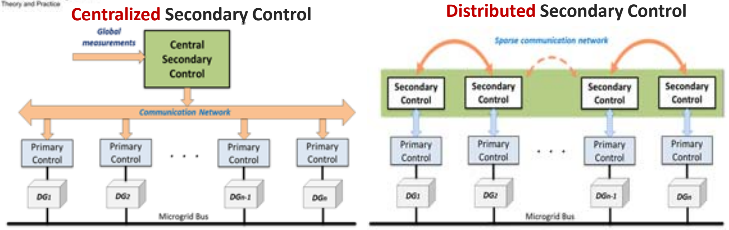
Power Quality Enhancement

Similar works…

- M. Savaghebi, A. Jalilian, J. C. Vasquez and J. M. Guerrero, "Autonomous Voltage Unbalance Compensation in an Islanded Droop-Controlled Microgrid," in *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1390-1402, April 2013.

1. M. Savaghebi, A. Jalilian, J. C. Vasquez and J. M. Guerrero, "Secondary Control Scheme for Voltage Unbalance Compensation in an Islanded Droop-Controlled Microgrid," in *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 797-807, June 2012.
2. A. Micallef, M. Apap, C. Spiteri-Staines, J. M. Guerrero and J. C. Vasquez, "Reactive Power Sharing and Voltage Harmonic Distortion Compensation of Droop Controlled Single Phase Islanded Microgrids," in *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1149-1158, May 2014.
3. F. Guo, C. Wen, J. Mao, J. Chen and Y. D. Song, "Distributed Cooperative Secondary Control for Voltage Unbalance Compensation in an Islanded Microgrid," in *IEEE Transactions on Industrial Informatics*, vol. 11, no. 5, pp. 1078-1088, Oct. 2015.
4. L. Meng *et al.*, "Distributed Voltage Unbalance Compensation in Islanded Microgrids by Using a Dynamic Consensus Algorithm," in *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 827-838, Jan. 2016.

Secondary Control Strategies



Centralized Control

- complex communication network; point to point com.
- easy implementing
- not straightforward scalability
- less reliability
- single point of failure

Decentralized Control?

Decentralized methods assume that the interaction between subsystems is negligible.

⇨ **They are not suitable for secondary control of Microgrids**

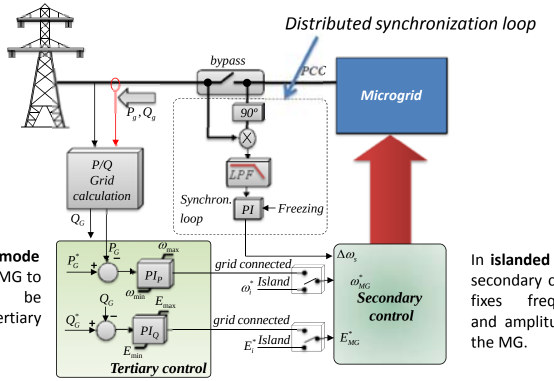
Distributed Control

- simple communication network; spars com.
- interaction between units
- easier scalability
- higher reliability
- Plug 'n' play capability

Tertiary Control

Tertiary control for AC microgrids

- Terciary control and synchronization control loops implementation



In **grid connected mode** P and Q from the MG to the grid can be controlled by tertiary control.

In **islanded mode** secondary control fixes frequency and amplitude of the MG.

Tertiary Control

Tertiary control for AC microgrids

- Tertiary control expressions

$$\omega_{MG}^{*} = k_{pP}\left(P_G^{*} - P_G\right) + k_{iP}\int\left(P_G^{*} - P_G\right)dt$$

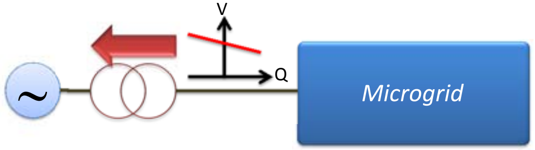
$$E_{MG}^{*} = k_{pQ}\left(Q_G^{*} - Q_G\right) + k_{iQ}\int\left(Q_G^{*} - Q_G\right)dt$$

- The tertiary control generates the frequency and amplitude references for the secondary control.
- The control expressions supose an highly inductive impedance on the grid side.
- Park transformation can be used for a general impedance case.

Tertiary Control

Tertiary control for AC microgrids

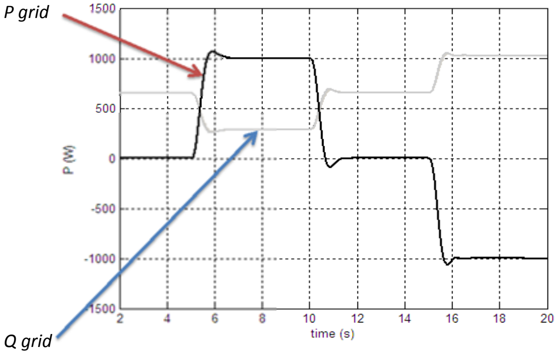
- Low voltage ride-trough of the Microgrid
  - *Freezing or disconnecting the integral term of the E – Q tertiary control.*
  - *The Microgrid will work like a STATCOM*
- *Energy Management Systems*



Tertiary Control

Tertiary control Example

Active power

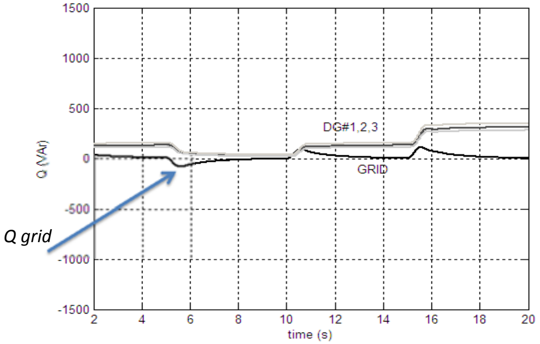


Pgrid changes and Q – ω tertiary control loop disconnected.

Tertiary Control

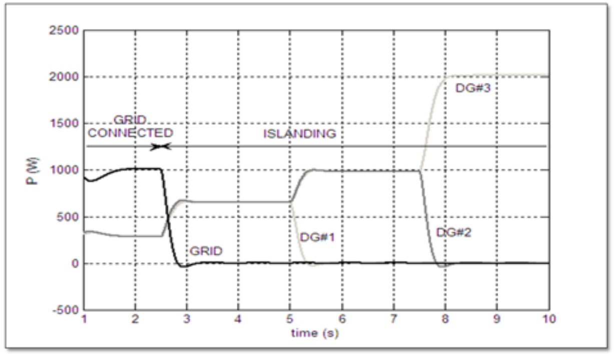
Tertiary control Example

Reactive power Q* = 0 VAr



Tertiary Control

Tertiary control example



Active power response. The tertiary control imposes *Pgrid* = 1 kW.

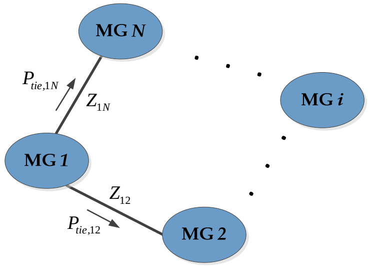
Microgrids Clusters

Microgrids interconnection

- ❑ In the islanded mode of operation, MGs, especially the ones highly dependent on renewable resources, may become unstable in the face of large sudden load/generation changes.

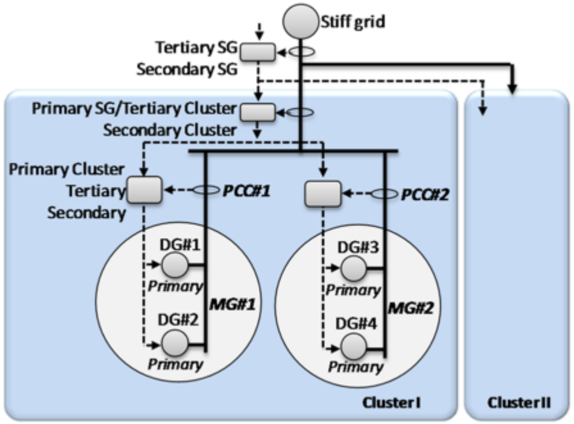
Interconnection of MGs is a solution to enhance:

- reliability,
- stability,
- supply security, and
- resiliency to disturbance.



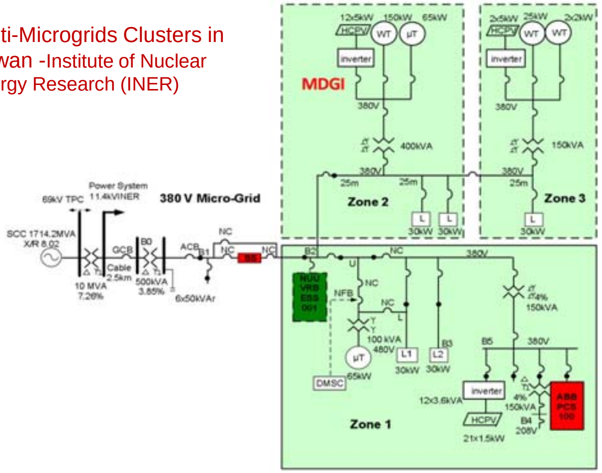
Microgrids Clusters

Microgrids interconnection



Microgrids Clusters Example

Multi-Microgrids Clusters in Taiwan -Institute of Nuclear Energy Research (INER)



Microgrids

Industrial/PhD course on Microgrids in Theory and Practice

Hierarchical Control

Conclusions

- Droop-controlled microgrids can be used in islanded mode.
- Improvements to the conventional droop method are required for integrate inverter-based energy resources:
  - Improvement of the transient response
  - Virtual impedance: harmonic power sharing and hot-swapping
- The hierarchical control is required for a AC microgrids:
  - Primary control is based on the droop method allowing the connection of different AC sources without any intercommunication.
  - Secondary control avoids the voltage and frequency deviation produced by the primary control. Power management, grid synchronization and power quality enhancement are other control objective introduced under the name of secondary control. This control level could be implemented either centralized or distributed.
  - Tertiary control allows to import/export active and reactive power to the grid.
- Interconnection of microgrids, or microgrids clusters, is a solution to enhance reliability, stability, supply security, and resiliency to disturbance.
- Additional features are also required to the flexible microgrids:
  - Voltage ride-through
  - Black-start operation
  - Grid impedance estimation
  - Storage energy management and control

Microgrids

Industrial/PhD course on Microgrids in Theory and Practice

Hierarchical Control

More References

[1] Visscher, K.; De Haan, S.W.H., “Virtual synchronous machines (VSG’s) for frequency stabilisation in future grids with a significant share of decentralized generation,” SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar, Volume , Issue , 23-24 June 2008 Page(s):1 – 4.

[2] A. Madureira, C. Moreira, and J. Peças Lopes, “Secondary Load-Frequency Control for MicroGrids in Islanded Operation”, in Proc. International,” Conference on Renewable Energy and Power Quality ICREPQ’05, Spain, 2005.

[3] J. P. Lopes, C. Moreira, and A.G. Madureira, “Defining control strategies for MicroGrids islanded operation,” IEEE Transactions on Power Systems, May 2006, vol. 21, no. 2, pp. 916- 924.

[4] B. Awad, J. Wu, N. Jenkins, “Control of distributed generation,” Elektrotechnik & Informationstechnik (2008) 125/12, pp. 409–414.

[5] A. Mehrizi-Sanir and R. Iravani, “Secondary Control for Microgrids Using Potential Functions: Modeling Issues,” Conf. Power Systems, CYGRE, 2009.

[6] K. Vanthournout, K. De Brabandere, E. Haesen, J. Van den Keybus, G.Deconinck, and R. Belmans, “Agora: distributed tertiary control of distributed resources,” in Proc. 15th Power systems Computation Conference, Liege, Belgium, August 22-25, 2005.

[7] J. M. Guerrero, J. C. Vasquez, J. Matas, L. García de Vicuña, and M. Castilla, “Hierarchical Control of Droop-Controlled AC and DC Microgrids – A General Approach Towards Standardization,” IEEE Trans Ind Electronics, 2010.

Microgrids

Industrial/PhD course on Microgrids in Theory and Practice

Thank you for your attention!

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Control Strategies for AC Microgrids

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Control Strategies for AC Microgrids

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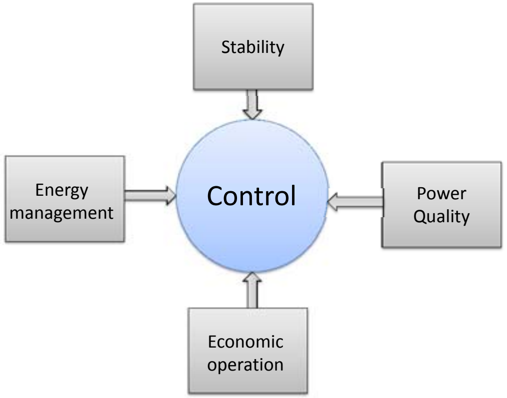
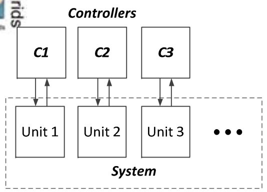
Outline

- Control Strategies in Microgrids
- Main Control Techniques Used in Microgrids
- Hierarchical Control
- Primary Control for microgrids
  - Droop Control
  - Modified Droop Control Methods
  - Non-Droop Control Methods
- Distributed Control
- Distributed Secondary Control
  - All-to-all averaging method-Gossip algorithm-Consensus protocol
- Distributed Tertiary Control
- Conclusions
- References

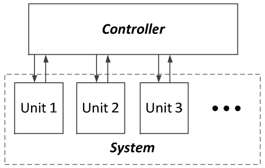
Control in Microgrids



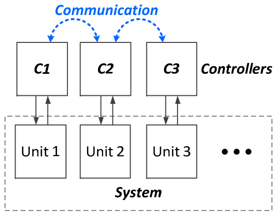
Control Strategies



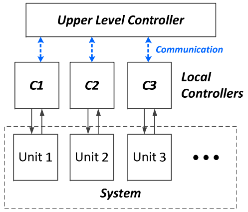
Decentralized Control



Centralized Control



Distributed Control

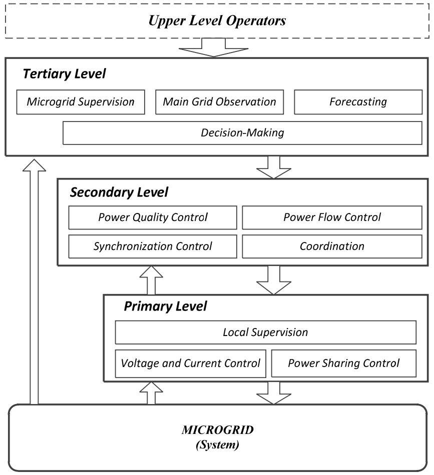


Hierarchical Control

Main Control Techniques Used in Microgrids

- ❑ **Linear Control**
  - Proportional-integral-derivative (PID), PI, proportional-resonant (PR)
- ❑ **Nonlinear Control**
  - Feedback Linearization, Gain Schedualing, Backstepping
- ❑ **Intelligent Control**
  - Fuzzy Logic, Neural Networks, Genetic Algorithms, Machine Learning
- ❑ **Robust Control**
  - H-infinity, H2, Sliding Mode, etc.
- ❑ **Optimal Control**
  - Model Predictive Control, LQG
  - Game Theory
- ❑ **Adaptive Control**

Hierarchical Control of Microgrids



Droop Control

- Basic idea of the droop control

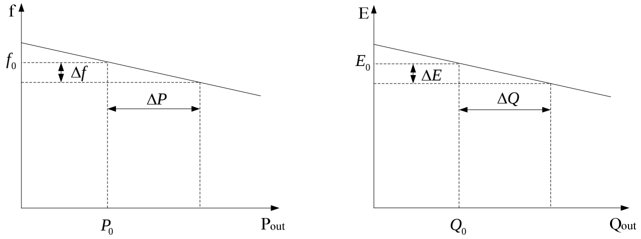
$$P = \frac{VE}{Z}\sin\delta\sin\theta + \frac{V}{Z}\left(E\cos\delta - V\right)\cos\theta$$

$$Q = \frac{V}{Z}\left(E\cos\delta - V\right)\sin\theta - \frac{VE}{Z}\sin\delta\cos\theta$$

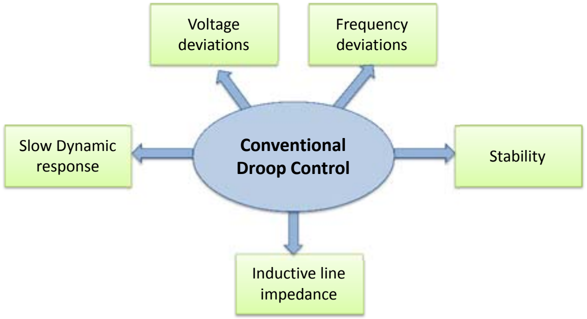
Simplifying assumptions:

$$\Delta P = \frac{VE_0}{X}\Delta\delta$$

$$\Delta Q = \frac{V}{X}\Delta E$$



Droop Control



Droop Control

❑ Conventional droop:

- Assumptions of inductive network impedance, small voltage angle
- Low pass filters for the calculation of active and reactive powers
- Fluctuation of system frequency with load changes

❑ Modified droop schemes:

- Improving the dynamic response by adding virtual impedance, derivate terms, etc. to the conventional droop.

❑ Alternative approach:

- Eliminate frequency deviations by using GPS timing technology
- Replace the power-based droop characteristics with a current-based droop to eliminate the delay associated with power calculation stage

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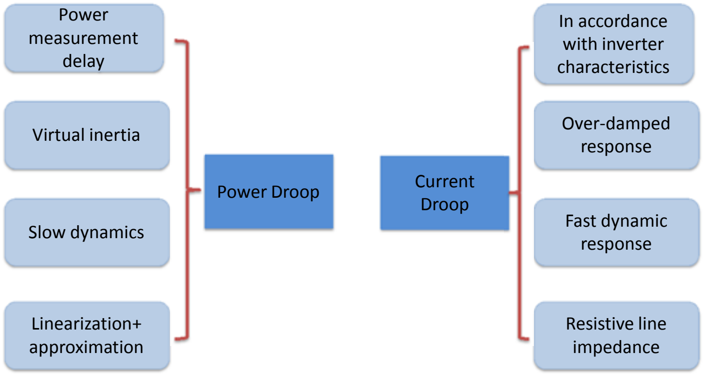
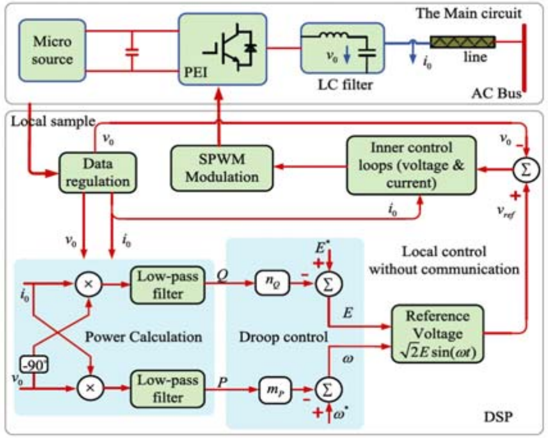
Droop Control



Power Droop:
- Power measurement delay
- Virtual inertia
- Slow dynamics
- Linearization+ approximation

Current Droop:
- In accordance with inverter characteristics
- Over-damped response
- Fast dynamic response
- Resistive line impedance

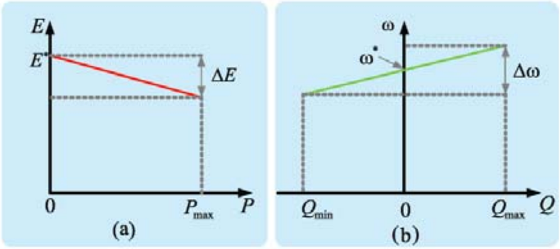
P-f & Q-V Droop Mechanisms



Source: H. Han, X. Hou, J. Yang, J. Wu, M. Su, J.M. Guerrero, ‘‘Review of power sharing control strategies for islanding operation of AC microgrids’’, IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 200–215, 2016.

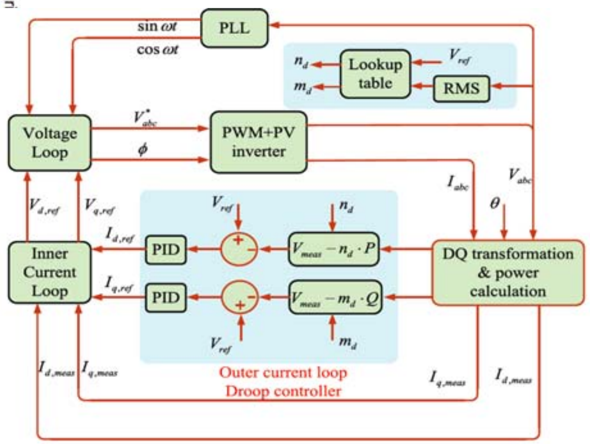
P-V & Q-f Droop Mechanisms

$$\begin{cases} \omega_i = \omega_{\text{rated}} + m_Q \cdot Q_i \\ E_i = E_{\text{rated}} - n_P \cdot P_i. \end{cases}$$



Source: H. Han, X. Hou, J. Yang, J. Wu, M. Su, J.M. Guerrero, ‘‘Review of power sharing control strategies for islanding operation of AC microgrids’’, IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 200–215, 2016.

P-Q-V Droop Mechanism



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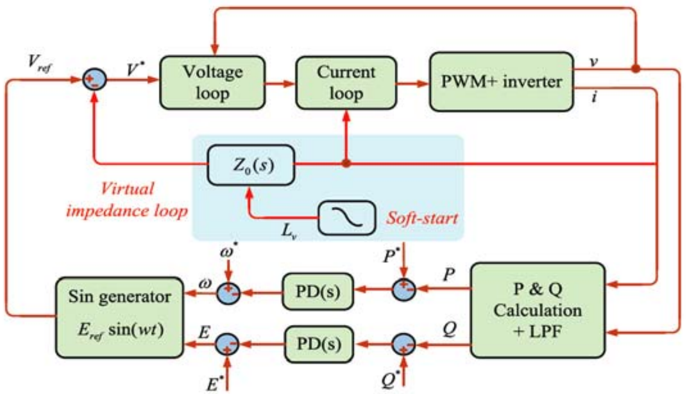
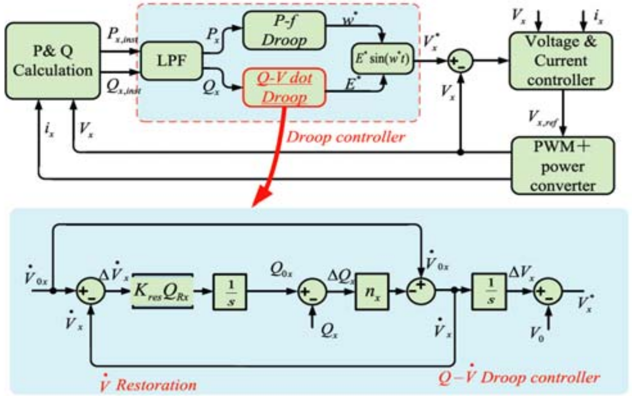
Droop Control with Virtual Impedance



Source: H. Han, X. Hou, J. Yang, J. Wu, M. Su, J.M. Guerrero, ‘‘Review of power sharing control strategies for islanding operation of AC microgrids’’, IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 200–215, 2016.

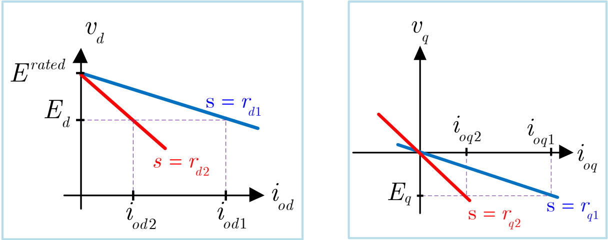
Q-V dot Droop Mechanism



Source: H. Han, X. Hou, J. Yang, J. Wu, M. Su, J.M. Guerrero, ‘‘Review of power sharing control strategies for islanding operation of AC microgrids’’, IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 200–215, 2016.

V-I Droop Mechanism

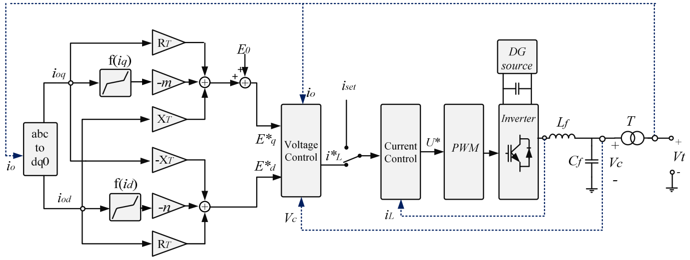
$$\begin{bmatrix} v^*_{cd} \\ v^*_{cq} \end{bmatrix} = \overbrace{\begin{bmatrix} E_0 \\ 0 \end{bmatrix}}^{\text{no load voltage}} + \overbrace{\begin{bmatrix} R_{gs} & -X_{gs} \\ X_{gs} & R_{gs} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}}^{\text{grid-side inductor drop compensation}} - \overbrace{\begin{bmatrix} r_d\, g(i_d) \\ r_q i_q \end{bmatrix}}^{\text{adaptive virtual resistance}}$$



Source: M. S. Golsorkhi and D. D. C. Lu, "A Control Method for Inverter-Based Islanded Microgrids Based on V-I Droop Characteristics," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1196-1204, Jun. 2015.

V-I Droop Mechanism

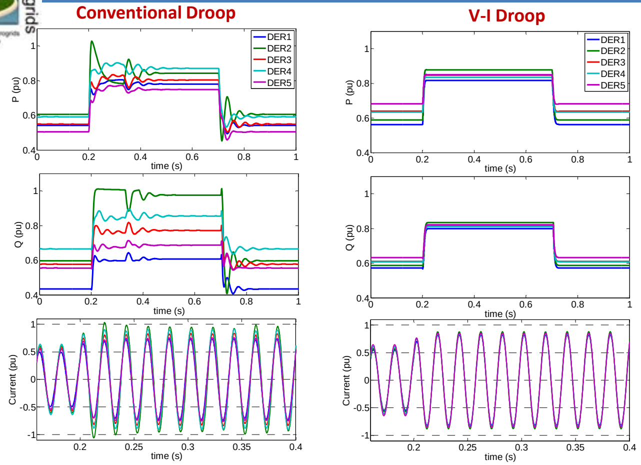
$$E_{qd}^{x} = \begin{bmatrix} E_0 \\ 0 \end{bmatrix} + \begin{bmatrix} R_{Tx} & X_{Tx} \\ -X_{Tx} & R_{Tx} \end{bmatrix} i_{xqd} - \begin{bmatrix} m_x g\left(i_{xq}\right) \\ n_x g\left(i_{xd}\right) \end{bmatrix}$$



- Frequency is fixed using GPS timing technology- Synchronization through GPS
- Droop characteristics works with high R/X ratio in microgrids
- Droop coefficient adaptively adjusted with the load

Source: M. S. Golsorkhi and D. D. C. Lu, "A Control Method for Inverter-Based Islanded Microgrids Based on V-I Droop Characteristics," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1196-1204, Jun. 2015.

V-I Droop Mechanism-Comparison Studies



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Decentralized Non-Droop Methods

Sources:

[1] M. S. Sadabadi, Q. Shafiee, and A. Karimi, “Plug-and-play voltage stabilization in inverter-interfaced microgrids via a robust control strategy strategy,” IEEE Trans. Control Syst. Technol., vol. 25, no. 3, pp. 781 - 791, 2017.

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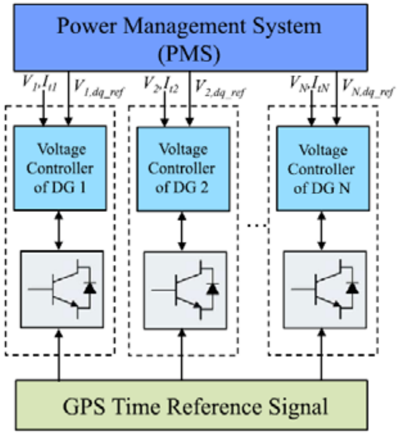
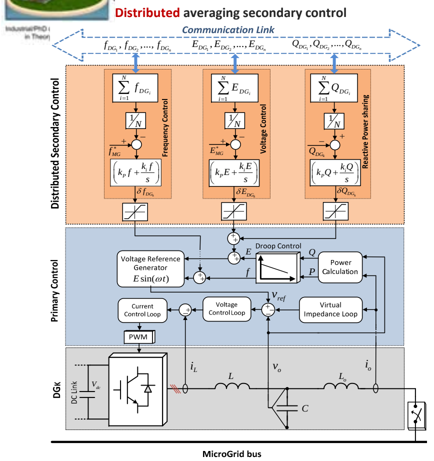
[3] S. Riverso, F. Sarzo, and G. Ferrari-Trecate, “Plug-and-play voltage and frequency control of islanded microgrids with meshed topology,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1176–1184, May 2015.



Distributed secondary control (all-to-all averaging method)



all-to-all averaging mehtod

$$\overline{x}_i = \frac{\sum_{i=1}^{N} x_i}{N}, \qquad i = 1,2,\ldots,N$$

$$\delta x_i = k_{px}(x^{ref} - \overline{x}_i) + k_{ix}\int (x^{ref} - \overline{x}_i)dt.$$

δx_i : the secondary controller output

x : can stand for frequency, voltage or power

$\overline{x}$: estimate of the global average of x

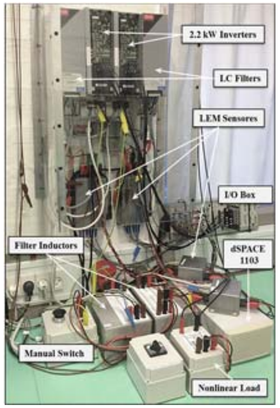
- ☐ Point-to-point communication is required; all the units need to be in communicate with each other.

Source: Q. Shafiee, J. M. Guerrero and J. C. Vasquez, "Distributed Secondary Control for Islanded Microgrids—A Novel Approach," in *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 1018-1031, Feb. 2014.

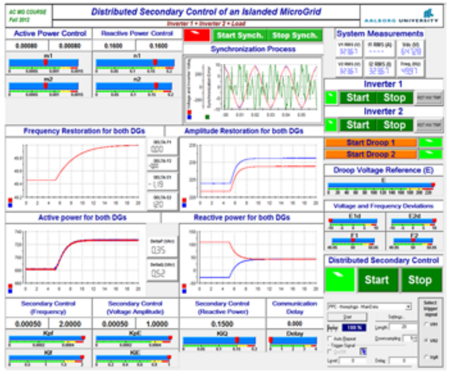
Distributed secondary control (all-to-all averaging method)

Experimental Validation

Experimental test system



dSPACE control desk



0.00080 0.00080 0.1600 0.1600

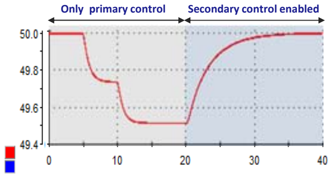
0.00050 2.0000 0.00050 1.0000 0.1500 0.000

Distributed secondary control (all-to-all averaging method)

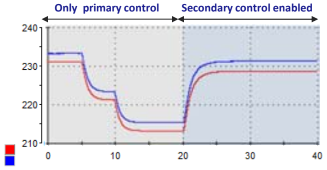
Experimental Validation

Performance of the proposed controller

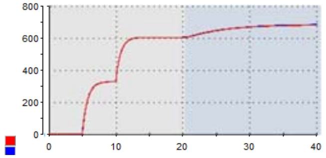
System frequency



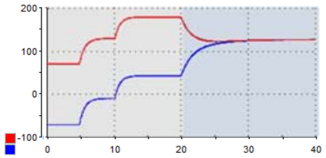
Voltage amplitude



Supplied active power



Supplied reactive power



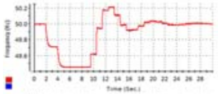
Distributed secondary control (all-to-all averaging method)

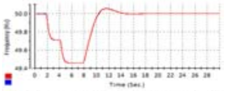
Impact of communication impairments (delay)

Time delay | Centralized secondary control | Distributed secondary control

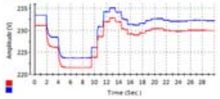
Fixed delay: 1 s
Variable delay: 0.5 s

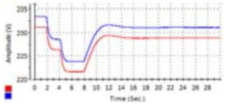
System frequency





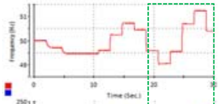
DGs voltage amplitude

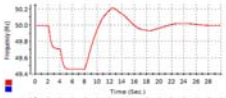




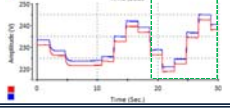
Fixed delay: 2 s
Variable delay: 0.5 s

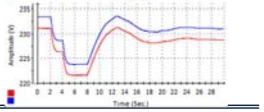
System frequency





DGs voltage amplitude





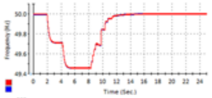
Distributed secondary control (all-to-all averaging method)

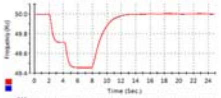
Impact of communication impairments (packet loss)

Packet loss | Centralized secondary control | Distributed secondary control

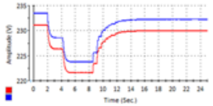
probability: 50%
delay: 100 ms

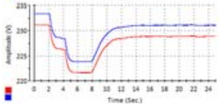
System frequency





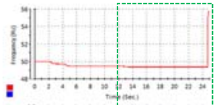
DGs voltage amplitude

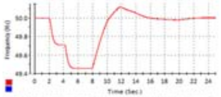




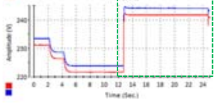
probability: 95%
delay: 100 ms

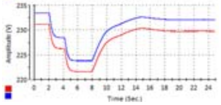
System frequency





DGs voltage amplitude





Distributed secondary control (a gossip algorithm method)

Objective: To estimate average value of needed information (voltage, frequency and reactive power).

The proposed gossip-based algorithm

The required averaged values ($\bar{f}$ … , $\bar{Q}_{MG}$) are defined as following:

$\bar{x}_i(k) = \beta_i x_i(k) + (1-\beta$ … $0,1,\dots,N-1$

$b(k) = \bar{x}_j(k)$ … $j = k \bmod N$

… $(l_i), l_i < k.$

β_i : … measurements $\beta_i = \frac{1}{N}$

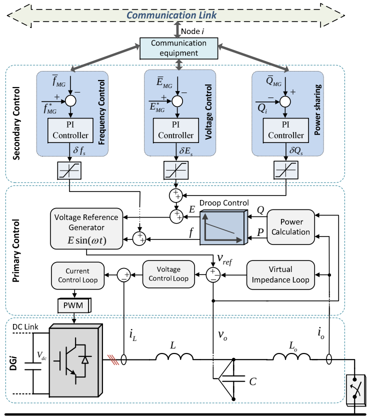
… and for frequency, voltage or power

x … al estimate of the global average of x

$b(k)$: signal broadcasted at k-th time instant

Asynchronous method; Synchronization and scheduling is required

- The gossip algorithm in connected networks converges to the average of initial node values [T. C. Aysal, M. E. Yeldiz, A. D. Sarwate, A. Scaglione, '09].

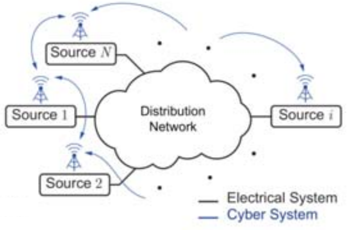


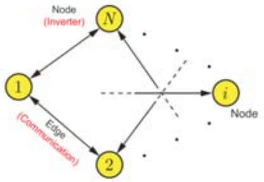
Source: Q. Shafiee, C. Stefanović, T. Dragičević, P. Popovski, J. C. Vasquez and J. M. Guerrero, "Robust Networked Control Scheme for Distributed Secondary Control of Islanded Microgrids," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 10, pp. 5363-5374, Oct. 2014.

Distributed control (consensus protocol)

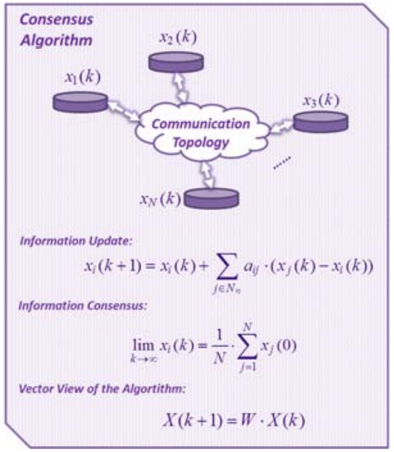
Consensus-based distributed control

- Synchronous method
- All nodes of the network activate at each time to update their current state .
- Prior knowledge of the system is not required.
- It requires spars communication.
- Scalability; It provides Plug-and-play capability.





Distributed control (consensus protocol)



Information Update:

$$x_i(k+1) = x_i(k) + \sum_{j \in N_n} a_{ij} \cdot (x_j(k) - x_i(k))$$

Information Consensus:

$$\lim_{k \to \infty} x_i(k) = \frac{1}{N} \sum_{j=1}^{N} x_j(0)$$

Vector View of the Algorithm:

$$X(k+1) = W \cdot X(k)$$

Information Consensus

Distributed control (consensus protocol)

A brief review on communication graphs

Set of nodes: $V = \{v_1, v_2, \dots, v_N\}$

Set of edges: $E \subset V \times V$

Adjacency matrix $A = [a_{ij}]$

$a_{ij} > 0$ if $(v_j, v_i) \in E$

$a_{ij} = 0$ otherwise

In-neighbors of the Node i $N_i = \{ j | (v_j, v_i) \in E \}$

Row sum=in-degree $d_i = \sum_{j=1}^{N} a_{ij}$, Col sum=out-degree $d_i^o = \sum_{j=1}^{N} a_{ji}$

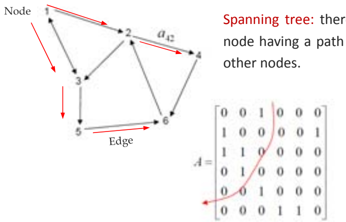
In-degree matrix $D = diag\{d_i\}$

Each node has an associated state $\dot{x}_i = u_i$

Standard local voting protocol $u_i = \sum_{j \in N_i} a_{ij}(x_j - x_i)$

Closed-loop dynamics $\dot{x} = Lx$

Laplacian matrix $L = D - A$



$$A = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Spanning tree: there is a node having a path to all other nodes.

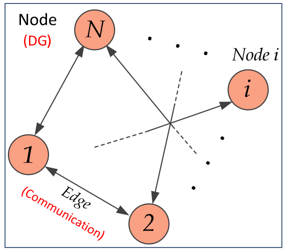
- A graph is balanced if in-degree=out-degree
- If graph has a spanning tree with a balanced Laplacian matrix, then consensus value is:

$x_i(t) \to \frac{1}{N} \sum_{j=1}^{N} x_j(0)$ = average of initial condition of nodes

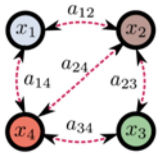
[R. Olfati-Saber & R. M. Murray, '04 ,'07]

Distributed control (consensus protocol)

communication graph

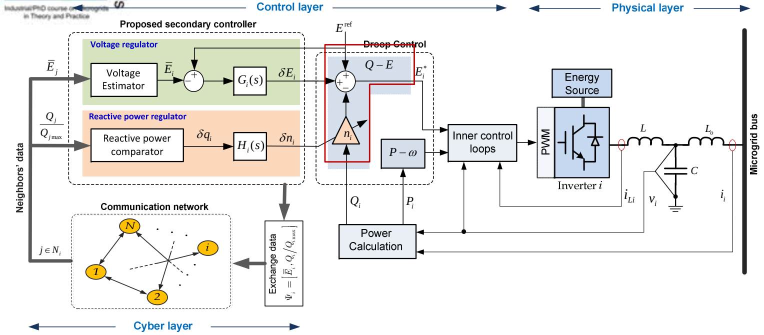


An example: ⇨



$$A=\begin{pmatrix}0 & a_{12} & 0 & a_{14}\\ a_{12} & 0 & a_{23} & a_{24}\\ 0 & a_{23} & 0 & a_{34}\\ a_{14} & a_{24} & a_{34} & 0\end{pmatrix}$$

Distributed secondary control (consensus protocol)



$$E_i = E^{ref} - n_i(t)\cdot Q_i + \delta E_i$$

Modified V-Q droop control

Source: Q. Shafiee, V. Nasirian, J. C. Vasquez, J. M. Guerrero, and A. Davoudi, "A Multi-Functional Fully Distributed Control Framework for AC Microgrids," *IEEE Trans. Smart Grid, 2017.*

Distributed secondary control (consensus protocol)

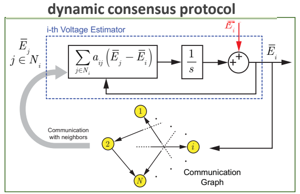
Voltage regulator

- Dynamic consensus protocol
- Averaged voltage estimator
- Regulates the voltage within an acceptable range
- Neighboring communication

Reactive power regulator

- Compares local generation with the neighbors'
- Adjusts local droop coefficient to mitigate the mismatch
- Proportional power sharing

dynamic consensus protocol



$$\overline{E}_i(t) = \int_0^t \sum_{j\in N_i} a_{ij}\left(\overline{E}_j(\tau) - \overline{E}_i(\tau)\right)\mathrm{d}\tau + E_i(t),$$

Reactive power comparator

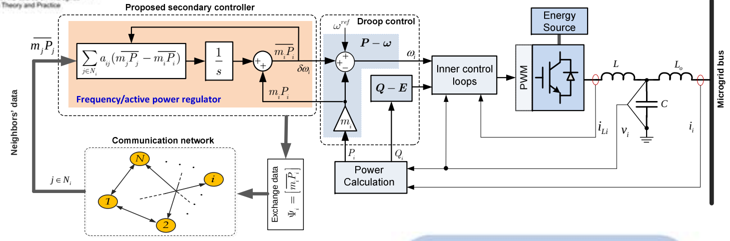
$$\delta q_i = \sum_{j\in N_i} ba_{ij}\left(\frac{Q_j}{Q_{j\max}} - \frac{Q_i}{Q_{i\max}}\right) = \sum_{j\in N_i} ba_{ij}\left(\frac{Q_j}{Q_{j\max}}\right) - b\left(\sum_{j\in N_i} a_{ij}\right)\frac{Q_i}{Q_{i\max}}.$$

$$n_i(t) = n_{i0} - \delta n_i(t).$$

Balance Laplacian matrix ⇨ $\lim_{x\to\infty} \overline{E}_i(t) = \frac{1}{N}\sum_{i=1}^{N} E_i(\mathrm{t}).$

Distributed secondary control (consensus protocol)

Frequency / active power regulation



- Frequency regulation
- Proportional power sharing
- No frequency measurements is required
- sparse communication
- distributed and modular
- Plug 'n' play implementation

$$\omega_i = \omega^{ref} - m_i\cdot P_i + \overline{p}_i$$

$$\overline{p}_i(t) = \int_0^t \sum_{j\in N_i} a_{ij}\left(\overline{p}_j(\tau) - \overline{p}_i(\tau)\right)\mathrm{d}\tau + p_i(t),$$

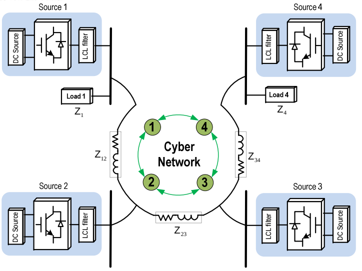
$$p_i(t) = m_i P_i(t)$$

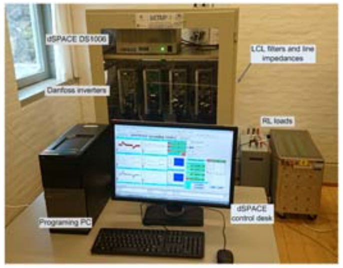
Balance communication graph

⇨ $\lim_{x\to\infty} \overline{p}_i(t) = \frac{1}{N}\sum_{i=1}^{N} p_i(\mathrm{t}).$

Distributed secondary control (consensus protocol)

Microgrid case study

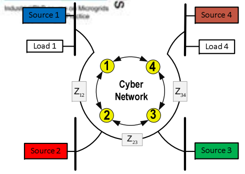




- **rated power** of sources 1&2 is twice of the other two.
- Rated voltage: **230 V** & frequency: **50 Hz**.
- distribution **line impedances** between the sources.
- cyber network to facilitate cooperation of units.
- **bidirectional** links to feature a balanced network; graphical connectivity in case of link/inverter failure

- 4 * 2.2 kW Danfoss inverters
- dSPACE DS1006
- LCL filters
- RL loads
- …

Distributed secondary control (consensus protocol)



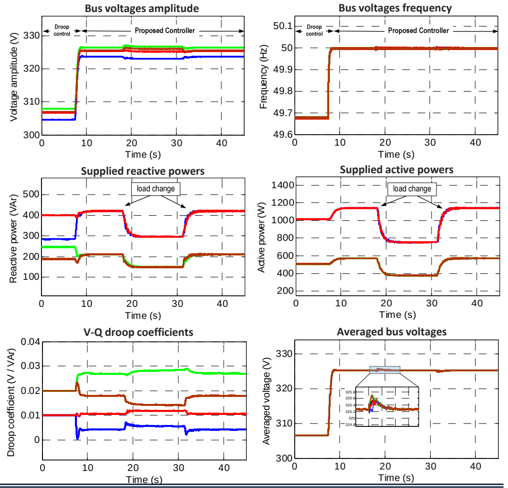
Cyber network: bidirectional

SC1 (t < 8s): Primary control is running

SC2 (t=8s): The proposed controller activated

SC3 (t=18s): Load 4 unplugged

SC4 (t=31s): Load 4 plugged back in



Bus voltages amplitude

Bus voltages frequency

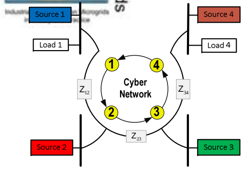
Supplied reactive powers

Supplied active powers

V-Q droop coefficients

Averaged bus voltages

Distributed secondary control (consensus protocol)



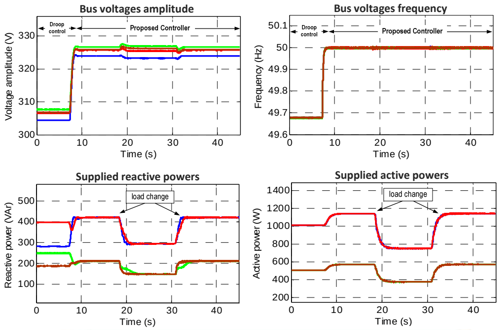
Cyber network: directed

SC1 (t < 8s): Primary control is running

SC2 (t=8s): The proposed controller activated

SC3 (t=18s): Load 4 unplugged

SC4 (t=31s): Load 4 plugged back in



Bus voltages amplitude

Bus voltages frequency

Supplied reactive powers

Supplied active powers

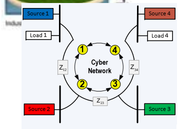
Comparing to study 1:

- ➢ Slower transient response
- ➢ The same steady-state response

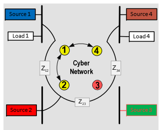
Generally:

- ➢ As long as communication network remain connected and balanced, any reconfiguration of cyber network does not affect the steady-state performance but the system dynamics.

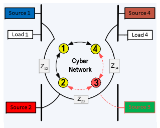
Distributed secondary control (consensus protocol)



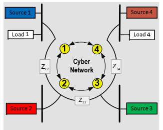
Scenario 1 (t<10s): All sources and the proposed controller operating.



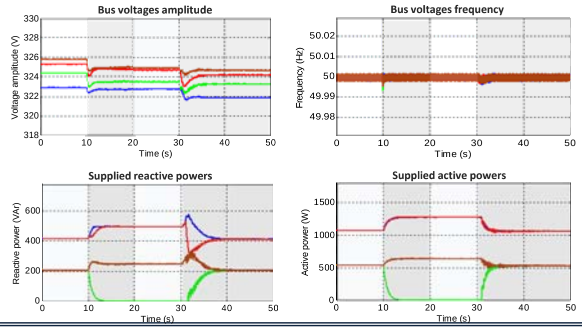
Scenario 2 (10s<t<20s): Source 3 is disconnected



Scenario 3 (20s<t<30s): synchronization process for source 3



Scenario 4 (30s<t<50s): source 3 is connected back. All sources operating

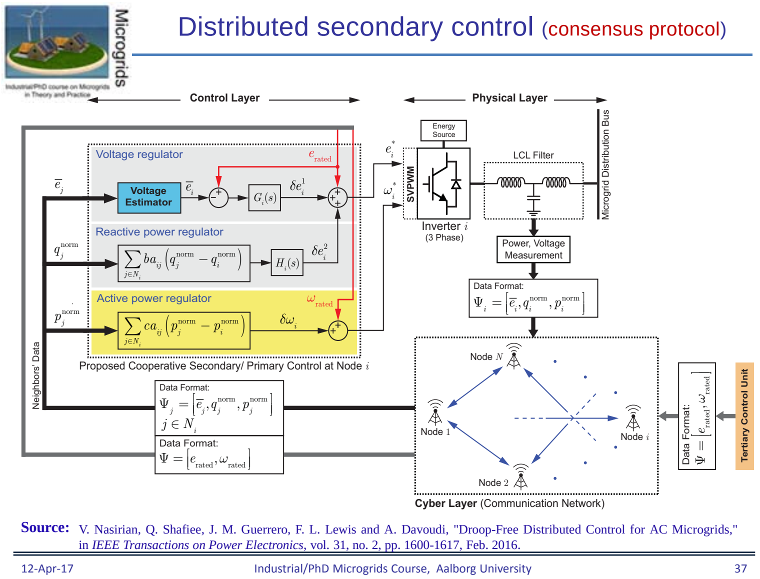


Bus voltages amplitude

Bus voltages frequency

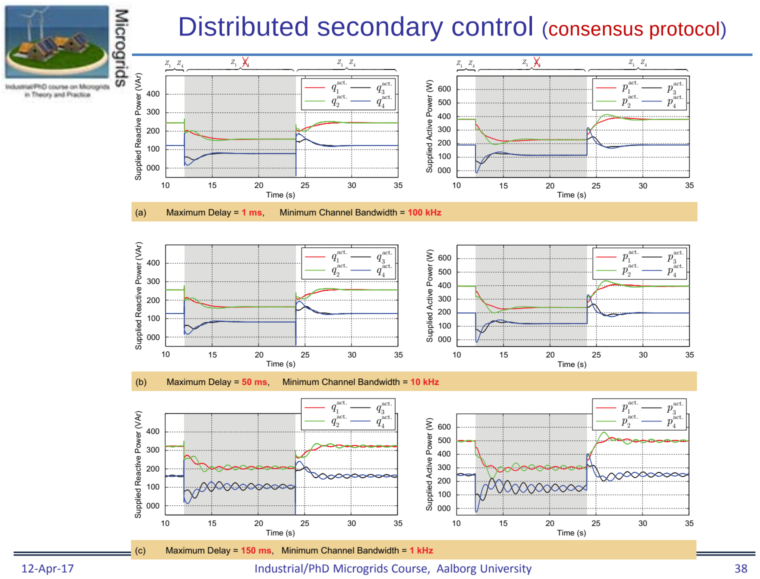
Supplied reactive powers

Supplied active powers



Distributed secondary control (consensus protocol)

Source: V. Nasirian, Q. Shafiee, J. M. Guerrero, F. L. Lewis and A. Davoudi, "Droop-Free Distributed Control for AC Microgrids," in *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1600-1617, Feb. 2016.

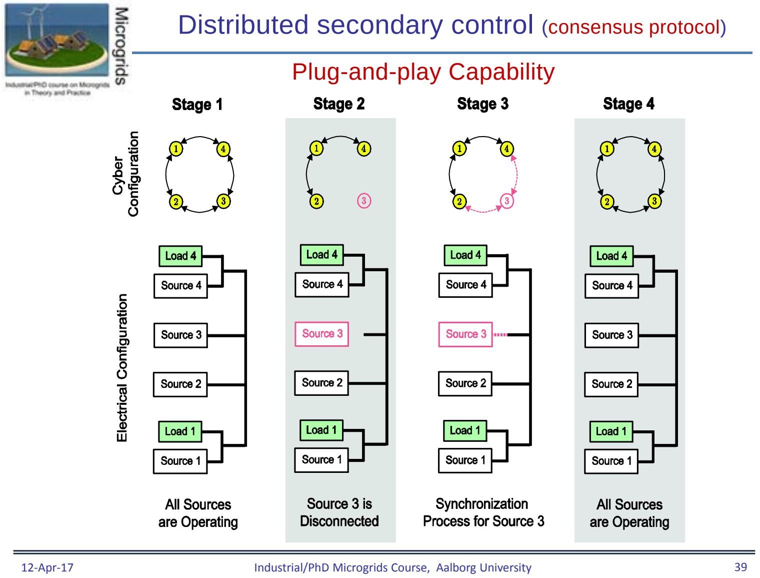


Distributed secondary control (consensus protocol)

(a) Maximum Delay = **1 ms**, Minimum Channel Bandwidth = **100 kHz**

(b) Maximum Delay = **50 ms**, Minimum Channel Bandwidth = **10 kHz**

(c) Maximum Delay = **150 ms**, Minimum Channel Bandwidth = **1 kHz**



Distributed secondary control (consensus protocol)

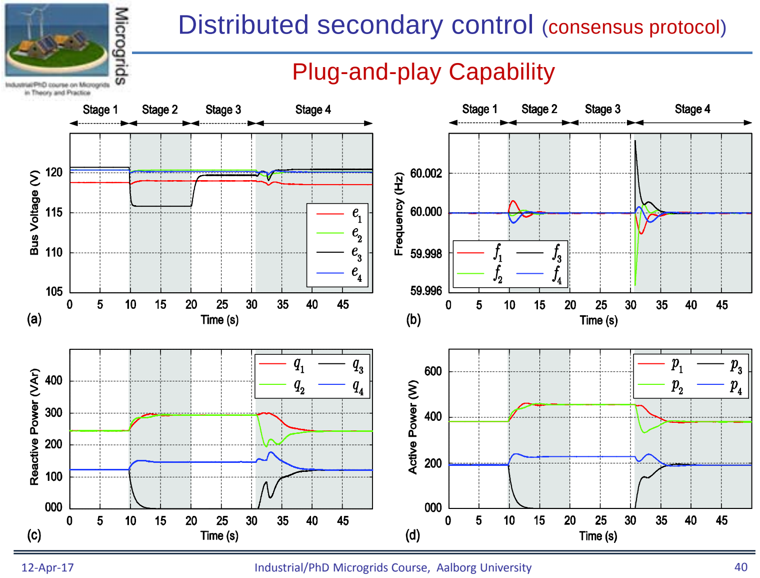
Plug-and-play Capability

Stage 1: All Sources are Operating

Stage 2: Source 3 is Disconnected

Stage 3: Synchronization Process for Source 3

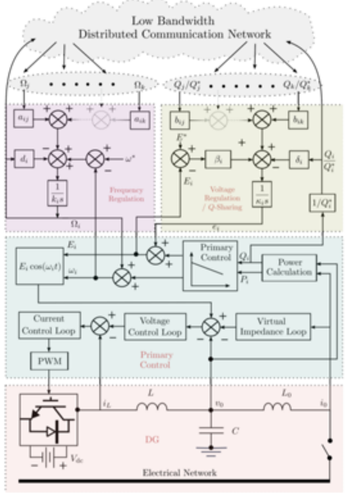
Stage 4: All Sources are Operating



Distributed secondary control (consensus protocol)

Plug-and-play Capability

Distributed secondary control (consensus protocol)



$$\omega_i = \omega^* - m_i P_i + \Omega_i\,,$$
$$k_i \frac{\mathrm{d}\Omega_i}{\mathrm{d}t} = -(\omega_i - \omega^*) - \sum_{j=1}^{n} a_{ij}\left(\Omega_i - \Omega_j\right),$$

$$E_i = E^* - n_i Q_i + e_i\,,$$
$$\kappa_i \frac{\mathrm{d}e_i}{\mathrm{d}t} = -\beta_i(E_i - E^*) - \sum_{j=1}^{n} b_{ij}\left(\frac{Q_i}{Q_i^*} - \frac{Q_j}{Q_j^*}\right),$$

Source:

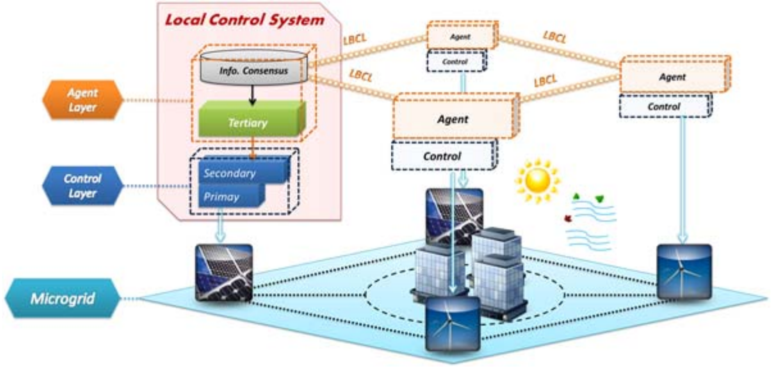
J. W. Simpson-Porco, Q. Shafiee, F. Dörfler, J. C. Vasquez, J. M. Guerrero and F. Bullo, "Secondary Frequency and Voltage Control of Islanded Microgrids via Distributed Averaging," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 7025-7038, Nov. 2015.

Distributed secondary control (consensus protocol)

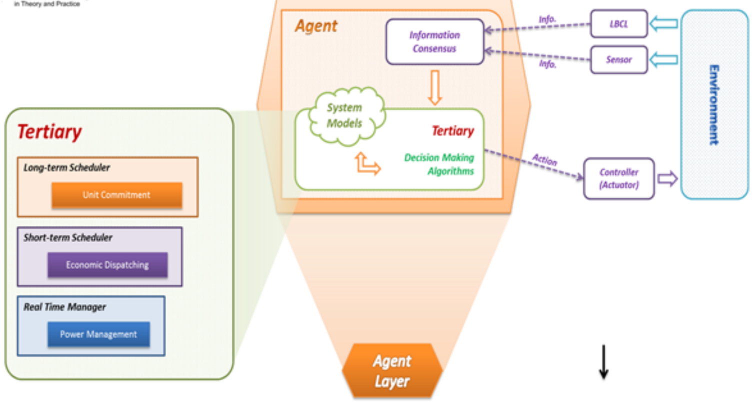
Similar works…

1. J. Schiffer, T. Seel, J. Raisch and T. Sezi, "Voltage Stability and Reactive Power Sharing in Inverter-Based Microgrids With Consensus-Based Distributed Voltage Control," in *IEEE Transactions on Control Systems Technology*, vol. 24, no. 1, pp. 96-109, Jan. 2016.
2. F. Guo, C. Wen, J. Mao and Y. D. Song, "Distributed Secondary Voltage and Frequency Restoration Control of Droop-Controlled Inverter-Based Microgrids," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4355-4364, July 2015.
3. A. Bidram, A. Davoudi, F. L. Lewis and J. M. Guerrero, "Distributed Cooperative Secondary Control of Microgrids Using Feedback Linearization," in *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3462-3470, Aug. 2013.
4. A. Bidram, A. Davoudi and F. L. Lewis, "A Multiobjective Distributed Control Framework for Islanded AC Microgrids," in *IEEE Transactions on Industrial Informatics*, vol. 10, no. 3, pp. 1785-1798, Aug. 2014.
5. A. Bidram, A. Davoudi, F. L. Lewis and S. Sam Ge, "Distributed Adaptive Voltage Control of Inverter-Based Microgrids," in *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 862-872, Dec. 2014.

Distributed Tertiary Control



Distributed Tertiary Control

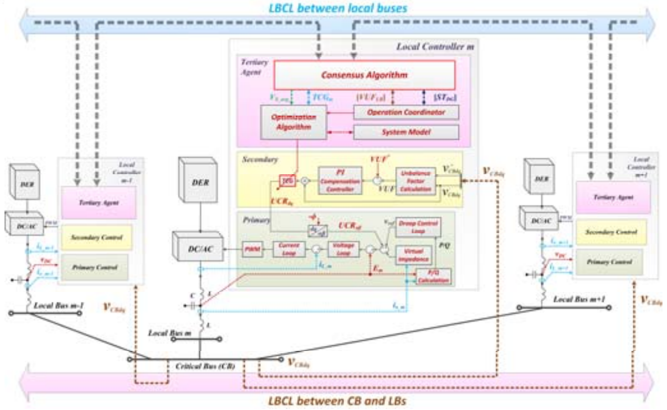


Microgrids

Industrial/PhD course on Microgrids in Theory and Practice

Distributed Tertiary Control

Example: Unbalance Compensation



Source: L. Meng, F. Tang, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, "Tertiary Control of Voltage Unbalance Compensation for Optimal Power Quality in Islanded Microgrids," IEEE Trans. Energy Convers., vol. PP, no. 99, pp. 1–14, 2014.

Microgrids

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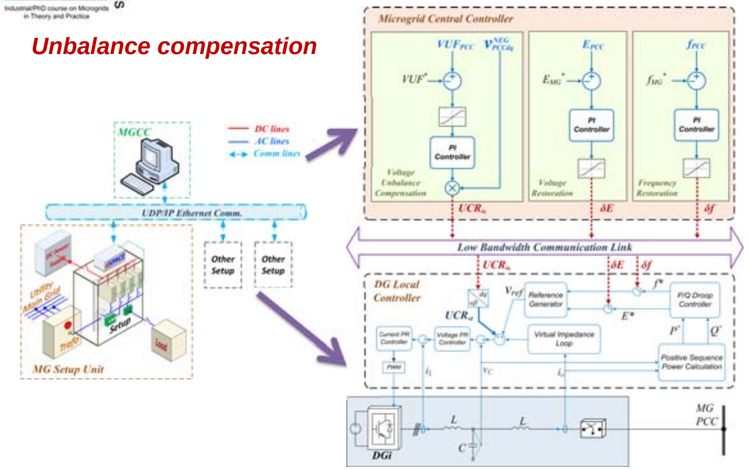
Distributed Tertiary Control

Unbalance compensation



Microgrids

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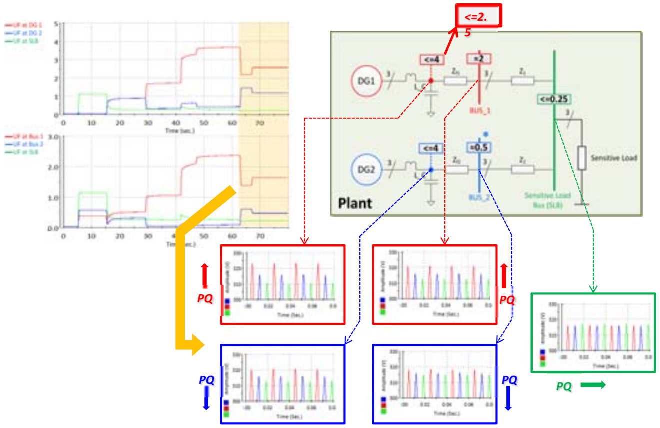
Distributed Tertiary Control

Unbalance compensation



Microgrids

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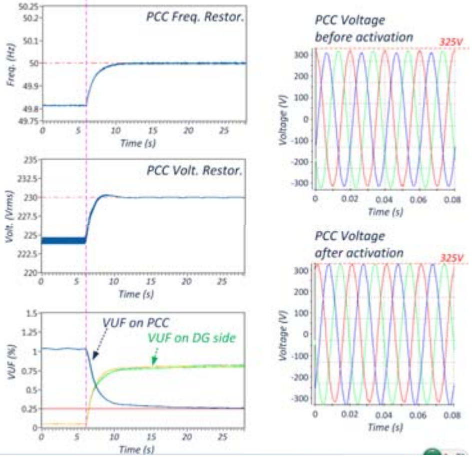
Distributed Tertiary Control

Unbalance compensation- Experimental Results



Hierarchical Control

Conclusions

- ❑ Control techniques used in microgrids are implemented in three different manners: decentralized, centralized and distributed.
  - Primary control methods are mostly decentralized.
  - Secondary control loops could be either centralized or distributed: distributed secondary control has attracted lots of interests, recently.
  - Tertiary control could be implemented in both centralized and distributed architectures.
- ❑ Linear control, nonlinear control, classic, and intelligent control techniques are used in microgrids.
- ❑ Advanced control methods are recently introduced for microgrids, however, linear control techniques (e.g., PI, PR) are still utilized in practice.
- ❑ Modified droop control methods and alternative approaches have been introduced to cope with the limitation of conventional droop mechanism.
- ❑ Non-droop approaches use GPS for synchronization of microgrids, and frequency control. They have complex structure and are not easy to implement comparing to the droop methods.
- ❑ Distributed control architectures have received a great deal of attention in microgrids.
- ❑ Distributed control architectures can discharge duties of a central controller while being resilient to faults or system uncertainties.
- ❑ Different distributed approaches have been presented for both secondary and tertiary control. They are often based on consensus protocol.
- ❑ Event triggered control technique is an alternative recently proposed for distributed control of microgrids, to reduce computation burden and communication costs.

Thank you for your attention!

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