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Advanced Control Architectures for Intelligent Microgrids

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Outline

1 Microgrids systems
2 Control of VSIs for microgrids
3 Droop control and virtual impedance concept
4 Hierarchical control of microgrids
5 Power quality in microgrids
6 DC microgrids
Centralized vs Distributed Power Systems

General advantages of the DPS:

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

Microgrid operation modes:

• Grid connected
• Islanded

Typical structure of a flexible microgrid
Microgrid operation modes

• Operation modes and transfers of the flexible microgrid and STS grid status supervisory
• Virtual inertias are often implemented through control loops known as droop method.
• Intelligent microgrids are required to integrate DG, DS, and dispersed loads into the future smart grid.
• Microgrids should be able to operate autonomously but also interact with the main grid.
• CSI units are normally used for PV or WT systems that require maximum power point tracker algorithms.
• VSI units are used for storage energy systems to support the voltage and frequency of the microgrid in island mode.
Islanded / Grid-connected operation

- Operation modes and transfers of the flexible microgrid and Static Transfer Switch (STS)

\[ P = P^*; \quad Q = Q^* \]
\[ \text{Import/export} \]
\[ P/Q \]

Current/Voltage Source

\[ STS = OFF \]

Grid Connected

\[ STS = ON \]

Islanding Operation

\[ E = V^* \]
\[ \omega = \omega^* \]

Voltage Source

Synchronization

\[ E = V_g \]
\[ \omega = \omega_g \]

From grid-connected an islanded modes, it is necessary a smooth transition.
For both modes, the converters could work as voltage sources!
Islanded operation

- Preplanned islanded operation: If any events in the main grid are presented, such as long-time voltage dips or general faults, among others, islanded operation must be started.
- Nonplanned islanded operation: If there is a blackout due to a disconnection of the main grid, the microgrid should be able to detect this fact by using proper algorithms.
Islanded operation

- **Voltage and frequency management**: The system acts like a voltage source, controlling power flow through voltage and frequency control loops adjusted and regulated as reference within acceptable limits.

- **Supply and demand balancing**: In grid-connected mode, the frequency of the DG units is fixed by the grid. Changing the setting frequency, new active power set points that will change the power angle between the main grid and the microgrid can be obtained.

- **Power quality**: The power quality can be established in two levels. The first is reactive power compensation and harmonic current sharing inside the microgrid, and the second level is the reactive power and harmonic compensation at the PCC; thus, the microgrid can support the power quality of the main grid.
Microgrid Configurations

- AC-DC Hybrid Microgrid
  Hierarchy of loads

Source: SMA

18-Aug-11
Microgrid Configurations

Connection interface (CI)
Inner control loops

Power stage and control of a 3 phase VSI with LCL filter

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \sqrt{2/3} \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
\]

Alpha-beta transformation
Inner control loops

Block diagram of the closed-loop VSI.

Voltage tracking

**Voltage control loop**

\[ G_v(s) = k_{pV} + \frac{k_{rV}s}{s^2 + \omega_o^2} + \sum_{h=5,7,11} \frac{k_{hV}s}{s^2 + (\omega_o h)^2} \]

Output impedance

**Current control loop**

\[ G_i(s) = k_{pl} + \frac{k_{rI}s}{s^2 + \omega_o^2} + \sum_{h=5,7,11} \frac{k_{hI}s}{s^2 + (\omega_o h)^2} \]

Computation delay

\[ G_{PWM} = \frac{1}{1+1.5T_s} \]

\[ V_c = \frac{G_v(s)G_i(s)G_{PWM}}{LCs^2 + (Cs + G_v(s))G_i(s)G_{PWM} + 1} V_{ref} - \]

\[ = \frac{1}{CS} \frac{1}{LCs^2 + (Cs + G_v(s))G_i(s)G_{PWM} + 1} i_o \]
Inner control loops

Bode diagram of the tracking voltage transfer function $G_v(s)$

Objective: closed-loop band pass filter characteristics with $0\,\text{dB},\ 0^\circ$

P+R

P+R+H

Objective: closed-loop band pass filter characteristics with $0\,\text{dB},\ 0^\circ$
Inner control loops

Results

abc-Voltages

abc-Currents
Control of parallel converters

Master-slave control

- Voltage source: grid forming units
- Current source: MPPT units. WT and PV

In this system is not necessary current sharing!
Control of parallel converters

Master-slave control

Woo-Cheol Lee “A Master and Slave Control Strategy for Parallel Operation of Three-Phase UPS Systems with Different Ratings”
Droop control for AC MGs

Droop control of AC systems

\[ \sin V E P X \phi = \]  

**Active power**  \[ P = \frac{V E}{X} \sin \phi \]  
**Reactive power**  \[ Q = \frac{E V \cos \phi - V^2}{X} \]

**Frequency droop**  
\[ \Delta \omega = \omega - \omega^* \]  
\[ \omega = \omega^* - mP \]  

**Amplitude droop**  
\[ \Delta E = E - E^* \]  
\[ E = E^* - nQ \]
Droop control for AC MGs

Inertias in power systems

- Synchronous generator

Equation of motion: 
\[ J \frac{d\omega}{dt} = T_m - T_e \]

Inertia constant: 
\[ H = \frac{\text{stored energy}}{\text{rating power}} = \frac{E}{P[s]} \text{ with } E = \sum \frac{1}{2} J \omega^2 \]

- Laplace Operator
- Mechanical torque (pu)
- Electrical torque (pu)
- Accelerating torque (pu)
- Inertia constant (MW-Sec/MVA)
- Rotor speed deviation (pu)

P. Kundur

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Inertias in power system

- Synchronous generator transient response

There is a dynamic and a static droop. The static droop coefficient is $\Delta P/\Delta f$. 
Virtual synchronous generators

- Inverters that mimic synchronous converters
- Kawamura’s approach (2005)

High Reliability and High Performance Parallel-Connected UPS System with Independent Control

Eduardo Kazuhide Sato

18-Aug-11
Virtual synchronous generators

Inertias means not only load-dependent frequency (droops), but also local storage energy system.

European Project VSYNC: http://www.vsync.eu
Droop control for AC MGs

Droop control of AC systems

- Trade-off power sharing / amplitude - frequency regulation

\[ \omega = \omega^* - mP \]

\[ E = E^* - nQ \]

\[ \Delta \omega_{\text{max}} = 2\% \]

\[ \Delta F_{\text{max}} = 5\% \]

Phase droops are not feasible since the initial phase of each inverter is different!
Droop control for AC MGs

Droop control of AC systems

Storage
$P < 0$

Generation
$Q > 0$

Capacitive load
$Q > 0$

Inductive load
$Q < 0$

$\omega$

$\omega^*$

$\Delta \omega$

$-P_{\text{max}}$
$P_{\text{max}}$

$E$

$E^*$

$\Delta E$

$-Q_{\text{max}}$
$Q_{\text{max}}$
Droop control for AC MGs

Generalized droop control

- Study of P/Q flow in function of the output impedance

By using the Park transformation, the droop method functions become:

\[
\begin{align*}
\omega &= \omega^* - m \left( P \sin \theta - Q \cos \theta \right) \\
E &= E^* - n \left( P \cos \theta + Q \sin \theta \right)
\end{align*}
\]

The R – V virtual resistance in a DC microgrid can be seen as Q – V droop in an inductive AC microgrid. The \( \omega – P \) droop is added to synchronize the system.
Virtual Impedance

Virtual Impedance concept

- Droop control in AC

Objective: fix the output impedance

Virtual Impedance concept...
Virtual Impedance

Soft-start operation

Initial PLL error
Output impedance

The virtual output impedance is a control variable.
Increasing the output impedance can reduce the initial current peak at the connection

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Virtual Impedance

**Hot-swap capability**

4 DG units microgrid

Before the connection, a PLL have to synchronize the DG with the MG. A the connection the virtual impedance is high to reduce the initial current peak.

This capability allow us to connect DGs without stop the microgrid, for maintenance reasons.
Low voltage ride-though

- Reactive power control of a grid-connected DG.

Trade-off during voltage dips: 1) voltage follower (Q=0) 2) stiff voltage source (Q high)
Low voltage ride-through

- Reactive power control of a grid-connected DG.

During the voltage grid, the converter injects reactive current (90°)
Low voltage ride-through

- Reactive power control of a grid-connected DG.

Active power remains constant (to the load). Reactive power is injected to maintain the voltage inside the droop characteristic.
Hierarchical control

Hierarchical Control Principle

Enterprise Software Solution for Power Systems

Primary Control

Tertiary Control

Secondary Control

Import/export power

Restoration/Syncro.

Inner loops (droop, softstart)

Enterprise Software Solution for Power Systems
Hierarchical control

Droop control for three phase VSIs

\[
\phi = \phi^* - G_p(s) \cdot (P^* - P) + \left( \frac{\omega_{\text{rest}} + \omega_{\text{sync}}}{s} \right)
\]

Three Phase Reference Generator \((\alpha \beta)\)

Power loops

Droop Control

Power Calculation

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Hierarchical control

Virtual impedance control for three phase VSIs

$$\begin{align*}
V_{V\alpha} &= R_v \cdot i_{o\alpha} - \omega L_v \cdot i_{o\beta} \\
V_{V\beta} &= R_v \cdot i_{o\beta} + \omega L_v \cdot i_{o\alpha}
\end{align*}$$

$$v_{\text{out}}(s) = G(s)v_{\text{ref}} - Z_o(s)i_o$$

$$Z_o(s) = \frac{1/C_s + G_v(s)G_i(s)G_{PWM}(s)}{LCs^2 + (Cs + G_v(s))G_i(s)G_{PWM}(s)+1} + L_v s$$
Islanding microgrids

- Grid-connected microgrids operate synchronized with the grid
- Islanded microgrids:
  - Frequency and amplitudes are load-dependent
- Secondary control can contribute to:
  - Frequency restoration
  - Amplitude regulation
  - Power quality (harmonics and unbalance compensation)

Energy management system can be used to:
- Load shedding
- Regulation of the generator’s consumption
Secondary Control in Electric Power Systems

This area consists of DG’s with the droop control. In island mode the frequency can droop down!
Secondary Control for Microgrids

Secondary control action

Primary control ensures $P$ sharing by drooping the frequency

Secondary control:
- Restore the nominal frequency
- Cannot work locally, it needs to be centralized.
Secondary control is located in the Microgrid Central Controller measure frequency and voltage. The output of the control is send through communications to adjust the reference of the local primary controllers (droops).
Microgrid synchronization with the grid

Synchronization is not necessary to be fast. **Slow** (to avoid unstability problems) but well **accurate** (allowing seamless transition to grid-connected mode).
Tertiary control for AC microgrids
• Tertiary 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 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
Microgrid example

Islanding detection

Non-planning Islanding

Frequency deviation

Islanding detection

STS open (protection)

Q integrators disconnected
Smart-Grids

Microgrids interconnection

Tertiary SG
Secondary SG
Primary SG/Tertiary Cluster
Secondary Cluster
Primary Cluster

Primary Cluster
Tertiary Secondary

PCC#1
PCC#2

DG#1
DG#2
Primary
Primary
MG#1

DG#3
DG#4
Primary
Primary
MG#2

Cluster I
Cluster II

Stiff grid

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Power Quality in Microgrids

Microgrids

- Fuel cell
- Source Bus
- PV
- Battery

Intermediate Supply Bus

UPQC Controller

PWM

PWM

Non-linear Load

Linear Load

Utility

Connection Bus

Utility Inverters and Loads

Load

Bus

Load

PWM

PWM

UPLC Controller

PWM

PWM

Advanced Active Filtering in a Single Phase High Frequency AC Microgrid - Sudipta Chakraborthy

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Droop control allows P and Q sharing, averaged over the fundamental frequency.

It is not able to guarantee harmonic current sharing!
Harmonics current sharing
• Control objective: Harmonic current sharing proportional to the nominal DG power.
• Trade off: harmonic current sharing/voltage THD

Source: Y. E. Wu
Harmonics current sharing

- For $Z_{\text{line1}} \neq Z_{\text{line2}}$, harmonic current sharing is not possible
- Harmonic virtual impedance can enhance sharing
  $$Z_h = \frac{V_h}{I_h}$$
- Trade off $V_{\text{THD}}$ and harmonic current sharing.
Power Quality in Microgrids

Droop control

*Virtual Output Impedance with harmonic current sharing loop*

Selective harmonic selection: fundamental and each of the harmonics can have different output impedance.
Power Quality in Microgrids

Harmonic current sharing

\[ H_i(s) = \frac{2k_i s}{s^2 + 2k_i s + \omega_i^2} \]

\[ Z_V(s) = I_{i1} \frac{2k_1 s^2}{s^2 + 2k_1 s + \omega_1^2} + \sum_{i=3}^{n} \sum_{k=1}^{3} \frac{2k_i s}{s^2 + 2k_i s + \omega_i^2} \]
Power Quality in Microgrids

Harmonic current sharing

**Fundamental**

Whole frequency range

**Harmonics**

Parallel Control of the UPS Inverters With Frequency-dependent Droop Scheme

*S. J. Chiang and J. M. Chang*
Power Quality in Microgrids

Droop method with virtual output impedance and selective harmonic

Wireless power-sharing controller
TMS320C6711 DSP board

Band-pass filters bank

Harmonic power-sharing loop

Resistive virtual impedance loop

Q-sharing loop

P-sharing loop

Reference generator

DSP implementation is appropriate for the multi-loop droop framework
Droop method for resistive output impedance

(a) Nonlinear load, Y: 2 A/div, X: 5 ms/div;
(b) Resistive // nonlineal load, Y: 10 A/div, X: 5 ms/div.
Power Quality in Microgrids

Voltage harmonic reduction by using current harmonics injection

\[ E_1 \angle \phi_1 \]
\[ Z_{o1} \]
\[ Z_{Line1} \]
\[ I_{h1} \]
\[ V_{PCC} \]

DG/MG

GRID

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Power Quality in Microgrids

Decentralized voltage harmonic reduction in an islanded microgrid
## Power Quality in Microgrids

### Decentralized voltage harmonic reduction in an islanded microgrid

<table>
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<tr>
<th>Voltage</th>
<th>Before Compensation</th>
<th>After Compensation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>THD%</td>
<td>5th %</td>
</tr>
<tr>
<td>DG1</td>
<td>3.8</td>
<td>2.9</td>
</tr>
<tr>
<td>DG2</td>
<td>2.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Load</td>
<td>5.3</td>
<td>4.2</td>
</tr>
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<table>
<thead>
<tr>
<th>Current</th>
<th>Before Compensation</th>
<th>After Compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THD%</td>
<td>5th %</td>
</tr>
<tr>
<td>DG1</td>
<td>58.6</td>
<td>53.7</td>
</tr>
<tr>
<td>DG2</td>
<td>45.8</td>
<td>41.5</td>
</tr>
<tr>
<td>Load</td>
<td>52.2</td>
<td>45.6</td>
</tr>
</tbody>
</table>

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Power Quality in Microgrids

Secondary control for voltage harmonic distribution in islanded microgrids

Diagram showing the connection of DG#1 and DG#2 to the AC Bus, with a Non Linear Load and Harmonic Controller for 5th and 7th Harmonics. Low Bandwidth Communications and PLL for synchronization are also depicted.
Harmonics in Microgrids

Secondary control for voltage harmonic compensation in islanded Microgrids
DG local controller (primary level)
Harmonics in Microgrids

Test system for secondary harmonic compensation

Diagram showing a test system with two DG sources, nonlinear and linear loads, and a PCC point for compensation.
Harmonics in Microgrids

Secondary control for voltage harmonic compensation

(a) Before amplitude restoration and harmonic compensation

(b) After amplitude restoration (no harmonic compensation)

(c) After amplitude restoration and harmonic compensation
Unbalance in Microgrids

Voltage unbalance definition

Voltage unbalance factor ($UF$) is considered as the index of unbalance. $UF$ can be defined as follows:

$$UF = \frac{v_{C_{\alpha\beta,\text{rms}}}^-}{v_{C_{\alpha\beta,\text{rms}}}^+}$$

where $v_{C_{\alpha\beta,\text{rms}}}^-$ and $v_{C_{\alpha\beta,\text{rms}}}^+$ are $rms$ values of negative and positive sequences of the DG output voltage.
Unbalance in Microgrids

Unbalance compensation for a grid-connected DG

\[ V_{dc} \]

\[ \alpha \beta \]

Current P+Resonant Controller

Voltage P+Resonant Controller

Virtual Impedance Loop

Positive and Negative Sequence Calculation

RMS Calculation

Power Calculation

Unbalance Compensation

Control System

PWM

Three phase Reference Generator \( E \sin (\phi^*) \)

Active Power Controller

Reactive Power Controller

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Unbalance in Microgrids

Unbalance compensation for a grid-connected DG

DG output Voltage
Unbalance in Microgrids

Decentralized unbalance compensation for a microgrid

[Diagram showing a microgrid system with various components labeled such as Voltage Resonant Controller, Current Resonant Controller, Virtual Impedance Loop, Positive and Negative Sequence Calculation, Power Calculation, Unbalance Comp., Active Power Controller, and Rective Power Controller.]

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Unbalance in Microgrids

Decentralized unbalance compensation for a microgrid

Unsymmetrical line

Voltage after and before compensation
Unbalance in Microgrids

Secondary control for unbalance compensation in islanded Microgrids

Secondary Controller
Low Bandwidth Communication Link
Unbalance in Microgrids

VUF at PCC and DGs terminal
\((CSG_1=CSG_2=1)\)

VUF at PCC and DGs terminal
\((CSG_1=1,CSG_2=1.25)\)

VUF at PCC and DGs terminal
(DG1 communication link failure at \(t=3.5\)sec)
Unbalance in Microgrids

Three-phase voltage waveforms

BEFORE COMPENSATION

AFTER COMPENSATION

PCC

DG1

DG2

(a) PCC-before comp.

(b) PCC-after comp.

(c) DG1-before comp.

(d) DG1-after comp.

(e) DG2-before comp.

(f) DG2-after comp.

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Conclusions

- Voltage harmonics in microgrids can be reduced by injecting current harmonic or adjusting harmonic voltage in the DG terminals.
- Secondary control can be used to close the loop of the harmonic voltage compensation in the microgrid.
- Tertiary control can be used to reduce the current harmonics injected by the microgrid to the grid.
- A ponderated trade off between the secondary and tertiary controls have to be designed.
- Unbalances in microgrids can be reduced by injecting a voltage negative sequence in the DG proportional to $Q$ negative sequence.
- Secondary control and tertiary control for unbalance compensation can be used for islanding and grid-connected microgrids.
- Reactive power have to be limited and ponderated for harmonics and unbalance compensation.
Distributed Energy Storage in Microgrids

Source: “Distribution Voltage Control for DC Microgrid with Fuzzy Control and Gain-Scheduling Control,” H. Kakigano et Al.
Adaptive droop control:

DC: \( V = V^* - (k/\text{SoC})I_o \)

AC: \( \omega = \omega^* - (k/\text{SoC})P \)

Extended Kalman Filters are used to obtain the SoC of the batteries.
<table>
<thead>
<tr>
<th>Name</th>
<th>Josep M. Guerrero (喬瑟輔)</th>
<th>Photo</th>
</tr>
</thead>
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<td>Email</td>
<td><a href="mailto:joz@et.aau.dk">joz@et.aau.dk</a></td>
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<td>Website</td>
<td><a href="http://www.et.aau.dk">www.et.aau.dk</a></td>
<td></td>
</tr>
</tbody>
</table>
| Educational Background | • 1993 ~ 1997. B.Sc Telecommunications Engineer (Technical University of Catalonia, Barcelona)  
• 1997 ~ 2000. M.Sc Electronic Engineer (Technical University of Catalonia, Barcelona)  
• 2000 ~ 2003. Ph.D Power Electronics (Technical University of Catalonia, Barcelona) |
| Work Experience | • Feb 1999 ~Aug 2004 Assistant professor (Technical University of Catalonia, Barcelona)  
• Sept 2004 ~Aug 2008 Lecturer professor (Technical University of Catalonia, Barcelona)  
• Sept 2008~Present Associate Professor (now part time) (Technical University of Catalonia, Barcelona)  
• July 2011~Present Full Professor (Aalborg University, Spain) |
| Autobiography |Josep M. Guerrero (S’01–M’04–SM’08) was born in Barcelona, Spain, in 1973. 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, Spain, in 1997, 2000 and 2003, respectively.  
He is part time Associate Professor with the Department of Automatic Control Systems and Computer Engineering, Technical University of Catalonia, where he currently teaches courses on FPGAs and control of renewable energy systems. From 2011 he is a Full Professor at the Institute of Energy Technology, Aalborg University, Denmark, and responsible of the Microgrid research program. He has been a visiting Professor at Zhejiang University, China, and University of Cergy-Pontoise, France. His research interests include power electronics converters for distributed generation and distributed energy storage systems, control and management of microgrids and islanded minigrids, and photovoltaic and wind power plants control. He is an associate editor of the IEEE Transactions on Industrial Electronics and IEEE Transactions on Power Electronics. He currently chairs of Renewable Energy Systems Technical Committee of IEEE IES. He is an elected IEEE IES Adcom member. |