Dual DC Buses Nanogrid with Interlink Converter

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Outline

- Introduction: From centralized to distributed generation.
- Types of residential nanogrids: AC or DC?
- DC bus voltages and number of buses.
- Control strategy for the DC nanogrids
  - DC bus signaling (DBS)
- Control strategies for the interlink (LV-HV) converter
  - Isolated and non-isolated high gain DC
  - Two-state and tri-state modulation strategies
- Fault detection and clearance in DC nanogrids.
Introduction (1/2)

- Conventional power system: Centralized.
- Load demand increases, then what?
- Environmental impact: Is renewables the solution?
- Dealing with the stochastic fluctuating nature of renewables…
- Distributed power generation: DG
- Issues of protection and power flow control.
Introduction (2/2)

- Concept of microgrids and intergrids.
- Autonomy and coordination of microgrids.
- Microgrids (neighborhoods) and nanogrids (homes).
- RES for co-generation and the net-zero energy home (NZEH).
- Impact of electric vehicles on the distribution systems.
- Linking EVs (picogrids) to residential nanogrids (V2H)?
Residential AC nanogrid (Boroyevich Optim10)
Residential nanogrids (1/2)

- Three-phase 4-wire (127:220V)...
- AC nanogrid: Good choice for a net-zero energy home?
- Sources and storage units are mostly DC.
  - DC-AC converters are used now.
- Modern appliances present an AC-DC converter, an unregulated DC bus followed by another DC-AC or DC-DC converter.
Residential nanogrids (2/2)

- What about a DC distribution system?
- Edison vs. Tesla revisited!
- Power electronics allow voltage level variations.
- DC-DC converters tend to be more efficient than DC-AC.
- Modern appliances are DC compatible. Remove AC-DC converter and PFC elements.
- No reactive power flow/demand.
- Conductors can be reduced for the some power transfer.
Residential DC nanogrid (Boroyevich Optim10)
Residential AC or DC nanogrid (Riccobono IEEE 16)
Choice of DC bus voltage

- Extra Low Voltage (ELV) DC presents a magnitude of less than 120 V and lower risk of electrical shock.
- 48V DC is a standard telecom voltage level.
- Supply of “kW” loads done with >20 A
- Issue with conductor size for reducing voltage drops…
- Following category is the Low Voltage (LV): <1500V.
- There is an “industry standard” at 380 V.
- Option of “dual DC bus system” promoted by EMerge Alliance: 24V & 380V.
EMerge Alliance

An open industry association leading the rapid adoption of safe DC power distribution in commercial buildings through the development of EMerge Alliance standards.

- Dual DC buses: 380 V + 24V/100W buses for lighting.
EMerge Alliance

EMerge Alliance® System Overview

AC Source

DC Source
- Solar
- Wind
- Fuel Cell
- Utility

DC Storage (Optional)
- Battery Array
- Flywheel
- Other

Power Supply Module (PSM)

Peripheral Load Cable Assy.

Window Shade Control

Lighting Load

Lighting Loads

PA Speaker

Bus Bar Component

Bus Bar Component with Internal Bus Bar

n Class 2 Channels @ 24 VDC, 100 Watts / 100 VA ea.

External Power Feed Connector (Typ.)
380 V DC eco-system development: Present status and future challenges (INTELEC 2013)

Figure 5: Vendors of 380V DC equipment and components at the time of writing.
Advanced LVDC electrical power architectures and microgrids (*Dragicevic, 2013*)
The dual DC buses nanogrid

- 48V for “low power” loads and 380 V for “higher power” loads.
- Generation and storage placed in both buses.
- Bidirectional interlink DC-DC converter.
Control strategy for the DC Nanogrids

- Hierarchical control:

- DC bus signaling (DBS) is used for coordinating the action of interfaces. \( I_o^* = f(V_o) \) or \( V_o^* = f(I_o) \). Variable DC bus voltage…

- Low bandwidth communication link for “regulation.”
DC bus signaling and droop control

- Droop control. Params: No-load voltage and droop slope

\[ I_{DC_x} = \frac{(V_{NL_x} - V_{DC})}{R_{d_x}} \quad R_{d_x} = \frac{\Delta V_{DC}}{\Delta I_{DC_x}} \quad I_{Load} = I_S + I_g + I_b \]
DC/DC Interlink Converter - Aniel Morais UFU

Interlink Converter

\[ n = 7.92 \]
Control strategies

• Usually the DBS is intended for supporting power balancing in one bus. Power injected into one bus will come from the other.

• **Option #1**: “Averaging” DBS efforts

\[
I_{inj\_LV} = I_{DBS\_LV} - I_{DBS\_HV} = \frac{V_{NL\_LV} - V_{DC\_LV}}{R_{d\_LV}} - \frac{V_{NL\_HV} - V_{DC\_HV}}{R_{d\_HV}}
\]

• **Option #2**: Equalize, by means of a PI controller, the % error between the voltages in the LV and HV bus.

• **Option #3**: Address the needs of the LV bus, until the HV bus is “stressed.”

\[
I_{inj\_LV} = \frac{V_{NL\_LV} - V_{DC\_LV}}{R_{d\_LV}}
\]

- \(I_{inj\_LV} \leq 0\), if \(V_{DC\_HV} > 390\) V
- \(I_{inj\_LV} \geq 0\), if \(V_{DC\_HV} < 370\) V
Interlink Converter control strategies

Average droop Control

\begin{figure}
\centering
\includegraphics[width=\textwidth]{average_droop_control}
\caption{Average droop Control diagram}
\end{figure}

Voltage limits are 0.947pu to 1.053pu
Interlink Converter control strategies

Constant voltage ratio control

Voltage limits are 0.947pu to 1.053pu

V380_pu

V48_pu

LPF

LPF

Kp_V

K

PI

Anti_Wind_up

I_ref_pu
Interlink Converter control strategies

**Average droop Control**

- Input: $V_{380\_pu}$, $V_{48\_pu}$
- LPF stages
- Output: $\frac{V}{2}$
- Gain $K = 0.5$
- Voltage limits are 0.947pu to 1.053pu

**Constant voltage ratio control**

- Input: $V_{380\_pu}$, $V_{48\_pu}$
- LPF stages
- Output: $\frac{Kp_V}{K}$
- PI control with anti-wind up
- Voltage limits are 0.947pu to 1.053pu
Interlink Converter control strategies

Average droop Control

Voltage limits are 0.947pu to 1.053pu

Constant voltage ratio control

Voltage limits are 0.947pu to 1.053pu
Simulation
Simulation

Load 1
Operate from 30 ms to 130 ms

Load 2
Operate from 80 ms to 180 ms
Simulated Converter

Dual Active Bridge Converter - DAB

Differential Voltage Control
- Equalize voltages between the two Buses

Bridge 2 Gate Signals, controlled by Phaseshift

Current Control

Bridge 1 Gate Signals

Power Calculations
# Averaged droop control

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![Graph showing droop control](image)

- Zone I: No Load
- Zone II: Load 1 (11.5 kW)
- Zone III: Loads 1 & 2 (17.3 kW)
- Zone IV: Load 2 (5.8 kW)

- 30 ms, 80 ms, 130 ms

---

This table and graph illustrate the averaged droop control for different zones with varying loads and no loads. The time intervals (30 ms, 80 ms, 130 ms) highlight the response and stability of the system under these conditions.
## Constant voltage ratio

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![Graph showing voltage ratio changes over time with different zones and load conditions.](chart.png)

- **Zone I**: No Load - 0 kW
- **Zone II**: Load 1 - 11.5 kW
- **Zone III**: Loads 1 & 2 - 17.3 kW
- **Zone IV**: Load 2 - 5.8 kW
- **No Load**: 0 kW

**Timings:**
- 30 ms
- 80 ms
- 130 ms
- 180 ms
DC-Bus Voltage

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30 ms  80 ms  130 ms  180 ms
Alternative control strategy (recall…)

• The interlink converter is controlled with DBS based (solely) on the voltage level of the LV DC bus (48V).
• Assuming that the HV DC bus (380 V) is connected to the AC utility grid, a strong system, it can provide/absorb power for balancing the HV DC bus.
• What if it is not active?
• The interlink converter is prevented from:
  – injecting power in the HV DC bus, if its voltage is higher than 390 V
  – Drawing power from the HV DC bus, if its voltage is lower than 370 V.
Loads vary $370 \, V \leq V_{HV} \leq 390 \, V$

Different load variations (time and value)
Loads vary with power shortage at HV bus
Loads vary with power surplus at HV bus
Alternative non-isolated high gain topology: 3-switch bidirectional DC-DC converter

Various possibilities of modulation schemes… tri-state!
Static Analysis

- Conventional (two-state) forward Buck-Boost:

  Fig. 6 Forward Buck-Boost:
  Voltage waveforms across switches $S_1$ and $S_2$

  Fig. 7 Forward Buck-Boost: Current waveforms in the switches

  Fig. 8 Forward Buck-Boost:
  Magnetizing inductance waveforms

  Fig. 9 Forward Buck-Boost:
  Voltage Conversion Characteristic

\[ \frac{V_2}{V_1} = \frac{D_1}{n(1-D_1)} \]
Tri-state 3-switch bidir. DC-DC converter

Research question: How can one benefit (and simplify) from this multivariable control scheme?

\[
\frac{V_2}{V_1} = \frac{d_3 + nd_1}{n^2(1-d_1) + n(1-d_3)}
\]
Tri-state 3-switch bidirectional DC-DC converter
5-switch bidirectional DC-DC converter
(Power flow direction changed without changing direction of $I_{LM}$)

$$\frac{V_2}{V_1} = \frac{D_2}{n(1-D_2)}$$

Buck-boost forward two-state
5-switch bidirectional DC-DC converter
(Buck-boost reverse two-state)

Various possibilities of modulation schemes: Tri-state, quad-state...
Performance of the two-state current control scheme of the 5-switch converter
Comparison of the two-state current control scheme of the 3- and 5-switch converter
Fault protection in DC nanogrids

• Fault detection and selective fault clearance.
• How to identify where the fault occur and which circuits breakers should open.
• Established technology for AC distribution systems.
• What about for DC nanogrids?
• Issue #1: Very small impedances between branches and nodes.
• Issue #2: Devices to open high DC currents. Arc extinction… Much more expensive, if available, than AC
• However, the power electronics interfaces provide some sort of control of the current injected into the DC bus…
Fault Current Limitation

- Traditional (tripping by overcurrent) vs. fault current limitation and interruption with coordination of interfaces and contactors. [3]
DC Ring-bus Microgrid Fault Protection and Identification of Fault Location (2013)
Configuration of a typical DC Nanogrid

Diagram showing the configuration of a DC Nanogrid with components labeled as follows:
- PV panel
- Battery
- Switches: Sw1, Sw2, Sw3, Sw4, Sw5
- Inductors: Lpv, Lb, LS
- Capacitor: C
- Resistor: R
- Voltages: vpv, vB, vs, vo
Prospective topology and control logic

• Normal operation: S1 ON and S3-S4 controlled as a classical current controlled class C converter.
• Fault current detected? Current control through S1 (PWM).
Control scheme
Experimental set-up
Experimental set-up
Experimental set-up
Droop, current limit and reduced current
Additional modulation schemes: Tri-state

- Conventional has 2 states, $D_{on}$ and $D_{off}$
- 3rd freewheeling state, $D_f$. Here $S2$ and $S4$ are On.
  
  \[ D_{on} + D_{off} + D_f = 1 \]

- Inductor is short-circuited. No transfer of energy.
- $D_{off}$ is kept constant to make $D_{on}$ the only control variable.
- Is there a “best sequence of states?”
Switch RMS Current Comparison

Forward power flow

Reverse power flow
Thank you for your attention!
Issues under investigation

- Control strategy for a single and a dual DC buses DC nanogrid.
- Hierarchical control with DC bus signaling (DBS) at the primary level.
- Control scheme for a solar PV converter operating in three modes: Droop, MPPT and current limiting. (AHMAD)
- Control of a hybrid energy storage system (HESS). Goal is to regulate a DC bus voltage, considering the power and energy density characteristics of batteries and supercapacitors. The attenuation of the voltage distortion caused by a single-phase AC grid interface is also considered. (ZAID)
- Control strategy for a bidirectional interlink DC-DC converter. (ANIEL-AHMAD).
- Fault protection. Choice of converter and logic for clearing faulted segments (SAROOSH).
Averaged droop control

Zone I

No Load
0 kW

30 ms
Averaged droop control

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30 ms 80 ms
### Averaged droop control

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### Graphs

- **30 ms**
- **80 ms**
- **130 ms**

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**Figure:**

- Load 1: Diagram showing power distribution.
- Load 2: Diagram showing power distribution.
- No Load: Diagram showing power distribution.

---

**Zones:**

- **Zone I:**
- **Zone II:**
- **Zone III:**
- **Zone IV:**
Constant voltage ratio

Zone I

No Load
0 kW

30 ms
Constant voltage ratio

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30 ms  80 ms
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30 ms 80 ms 130 ms
Zaid
Configuration of a Basic DC Nanogrid

Hybrid Energy Storage System (HESS)
Conventional HESS control scheme

Outer voltage loop

Inner current loop

Inner current loop
The MPPT Scheme

- The MPPT scheme is based on linearity ($K_p$) between the optimization current and the maximum output power of the PV.

- The maximum power prediction line is used to estimate the maximum power the PV can generate for a measured (instantaneous) current.

- The solar converter operates at MPPT by comparing this estimated maximum power with the power generated from the PV.
Case Study
Simulation and Results

- MATLAB/Simulink

- A 5 kW PV array \( (V_{\text{MPPT}} = 232 \text{ V} \text{ and } I_{\text{MPPT}} = 22 \text{ A}) \) was modeled in MATLAB.

- Solar converter supplying the load in stand-alone

- Solar converter and grid interface converter together
Solar converter supplying the load in stand-alone
Solar converter and grid interface converter together