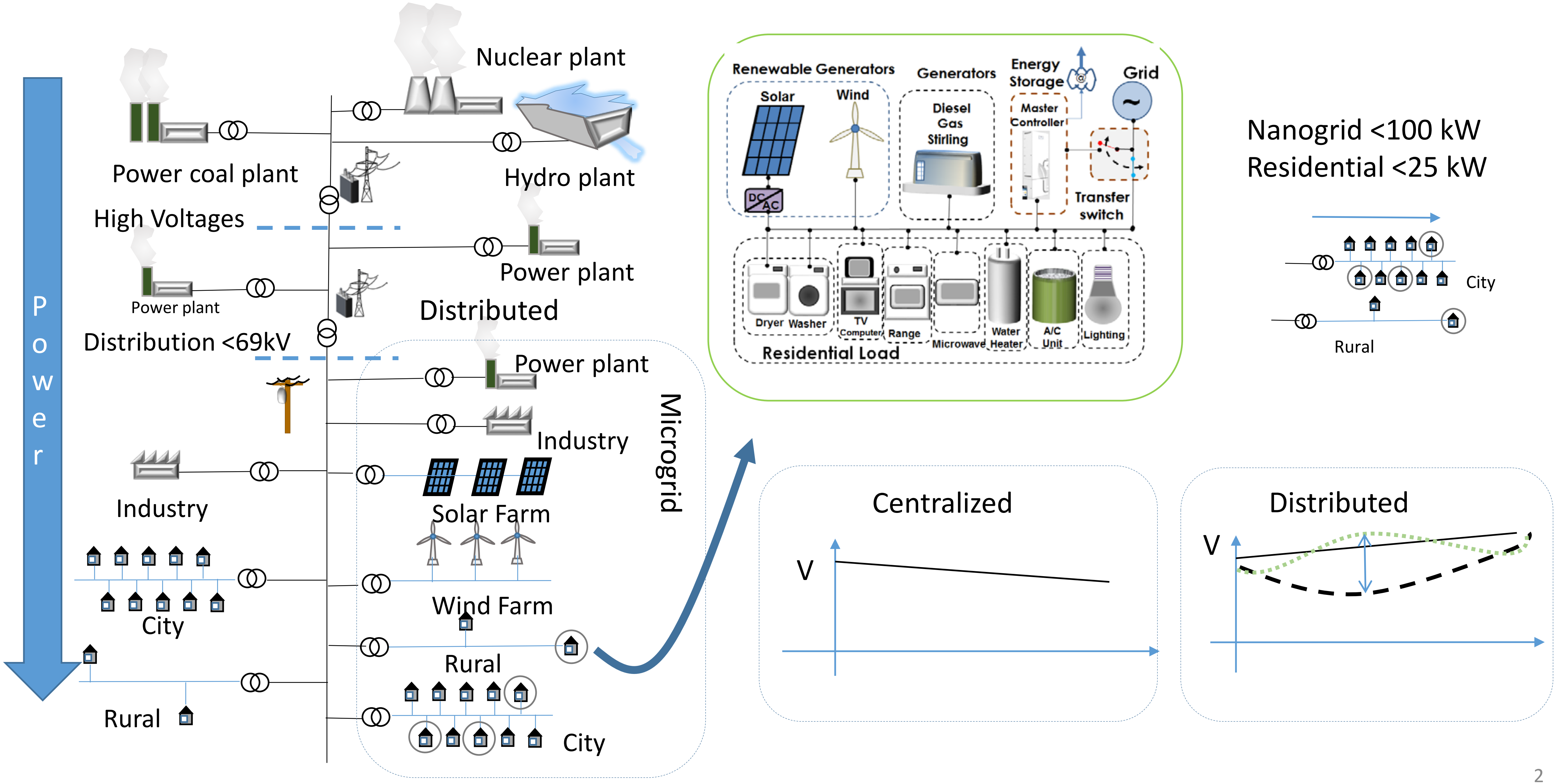
Residential Battery Storage: The cornerstone of the Nanogrid and distributed power systems

Antonio Ginart

Santa Clara, California

Power System Centralized vs. Distributed



Distributed Paradigm Shift - Renewables

Disadvantages

- ❑More complex technologies
- ❑More expensive in many cases
- ❑Less centralized control
- ❑Potential for a less reliable grid
- ❑Need of new technology and regulations
- ❑Potential for greater power quality issues




Advantages

- ❑Potential for better local resource use
- ❑Consumers have greater independence
- ❑Environmentally friendlier
- ❑Potential for a more robust and reliable grid (non-single collapse point)
  - ❑Cybersecurity
  - ❑Natural disaster
- ❑Potential for more economically sound macro-analysis

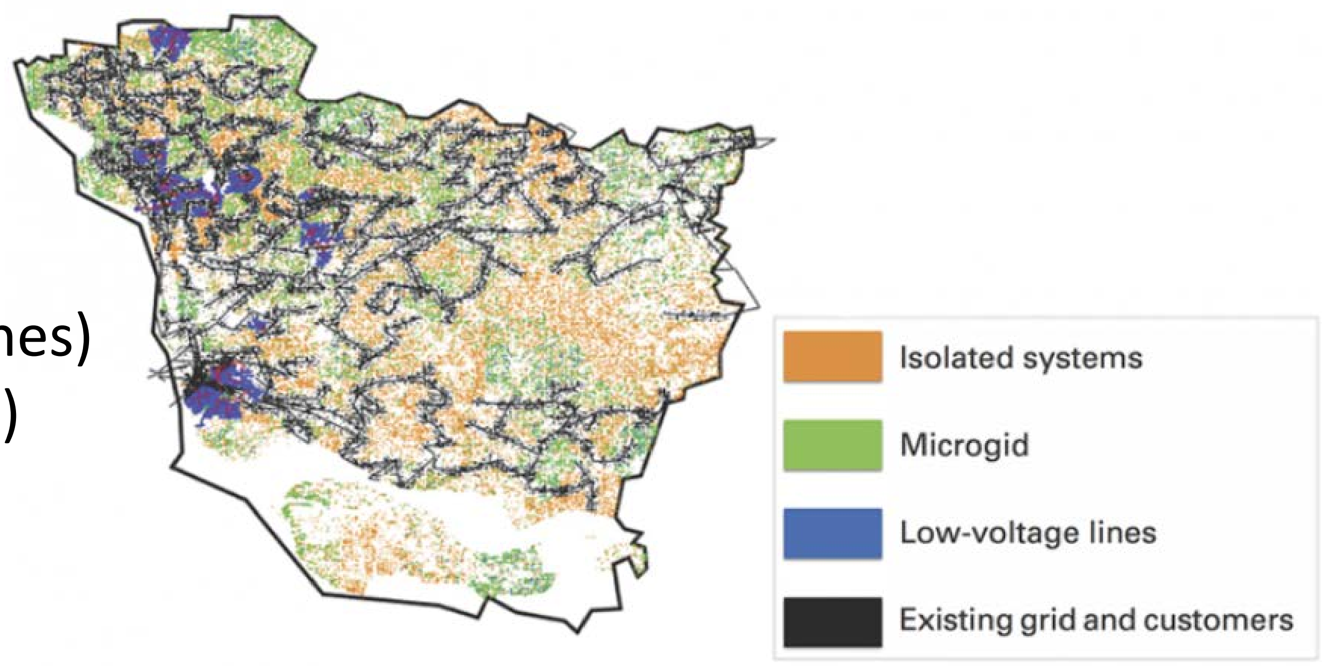
Minimum-cost of Electrification

Electrification Model (REM)

400,000 non-electrified buildings in the Vaishali district of Bihar, India.

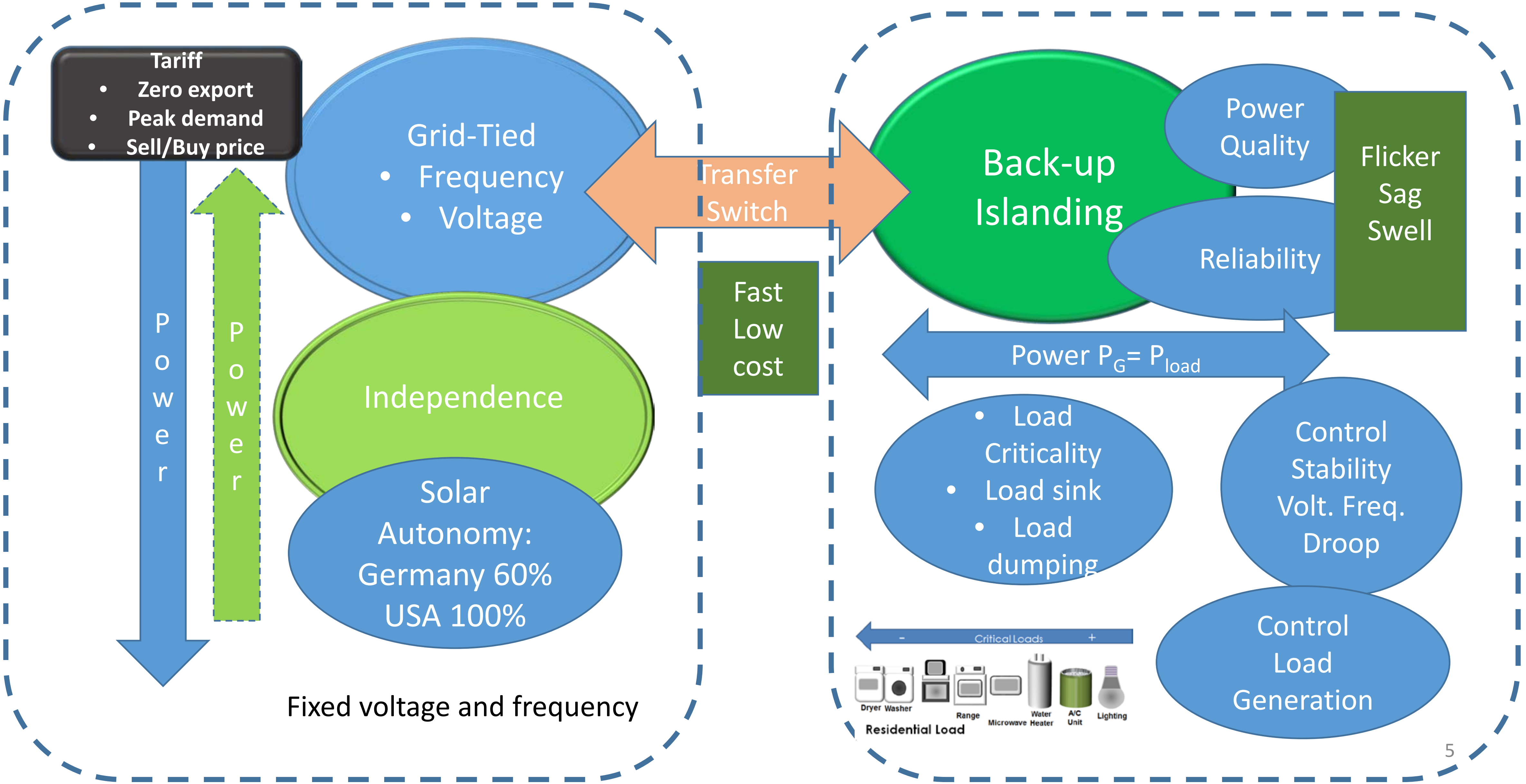
Options

- ❑ Grid extension (low-voltage lines)
- ❑ Stand alone system (Nanogrid)
- ❑ Microgrid

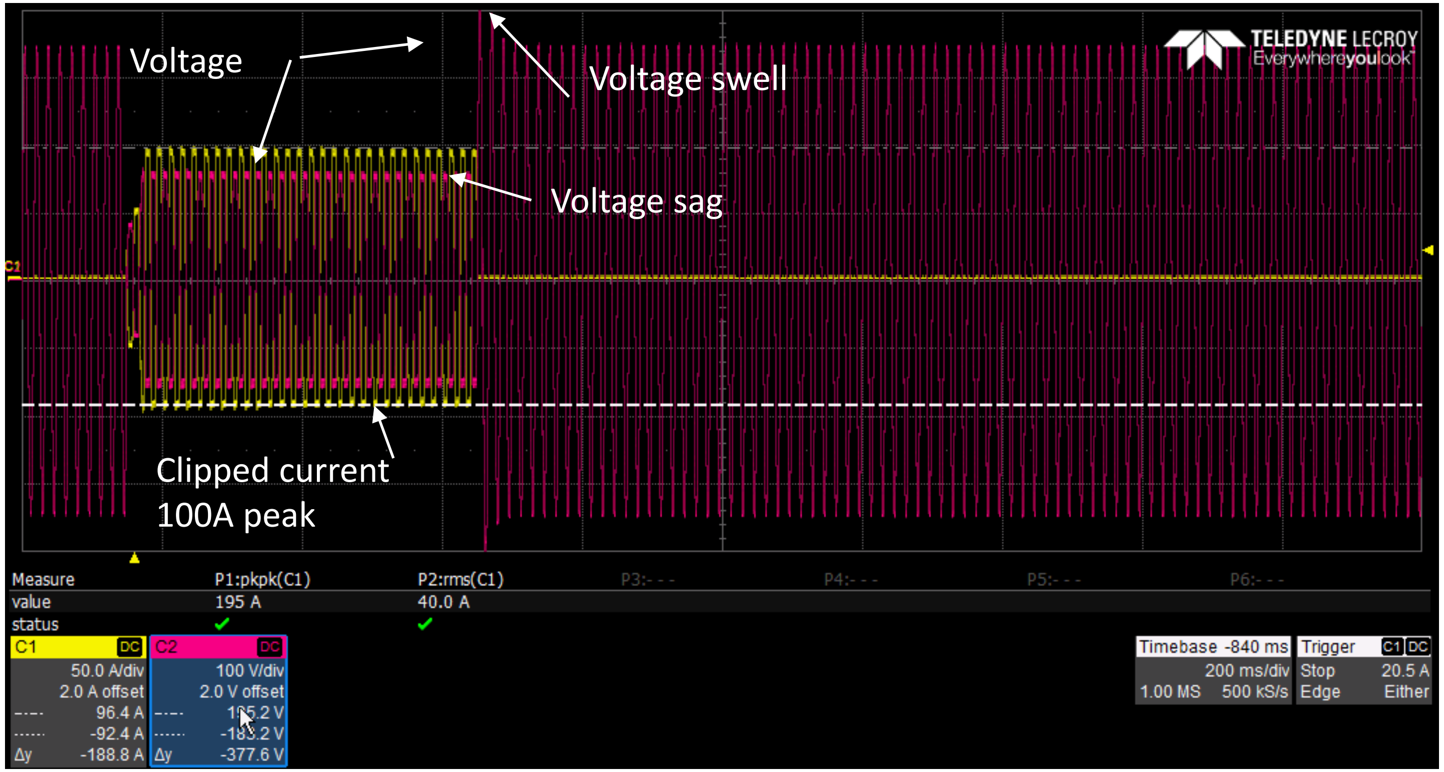


MIT News (January 2016)

Nanogrid Operation Mode



Power Quality Issues (Back up Mode)



Line voltages under A/C 5 TON system start up

		½ cycle 8.3ms	1 cycle 16.6ms	3600 cycles 60 s	>3600 cycles > 60 s
1	Transients				
2	Sag and swell				
3	Noise				
4	Harmonics				
5	Under and over Voltages				

The standard IEEE 1100

- Short term voltage variations (sag ,swell, and transients)
- Long term voltage variations (over and under voltages , harmonics and noise)

Residential Nanogrid
DC-AC

DC Nanogrid

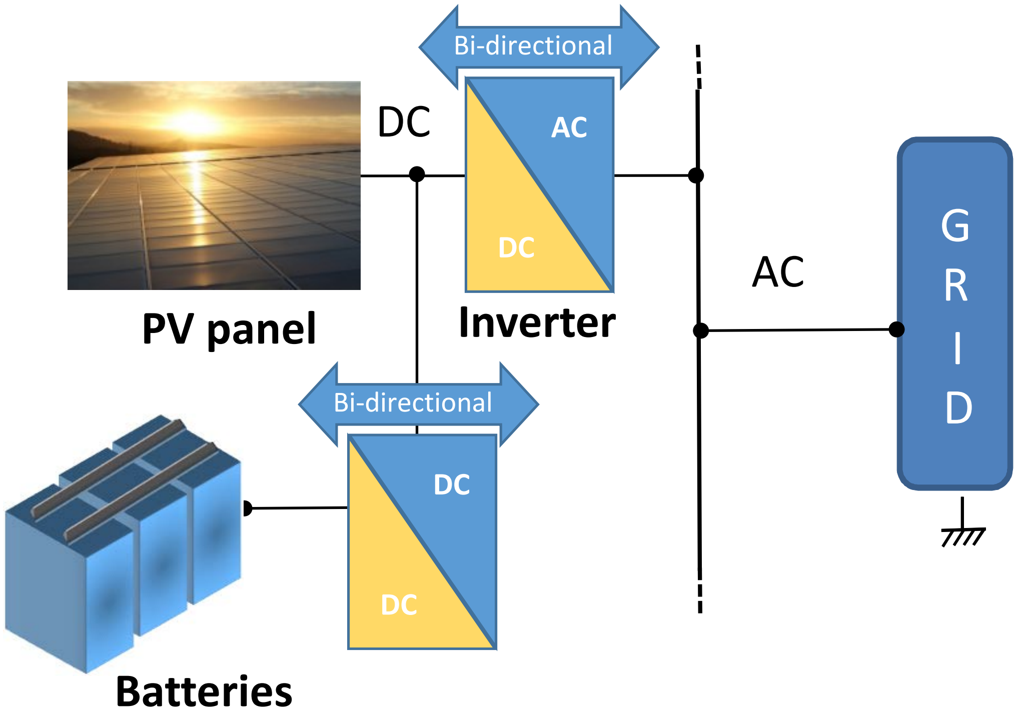
- 12V- 400V
- Advantages
  - More efficient
  - Easy control, stable
- Disadvantages
  - Large investment required
  - Difficult interruption (protection, fire)

AC Nanogrid

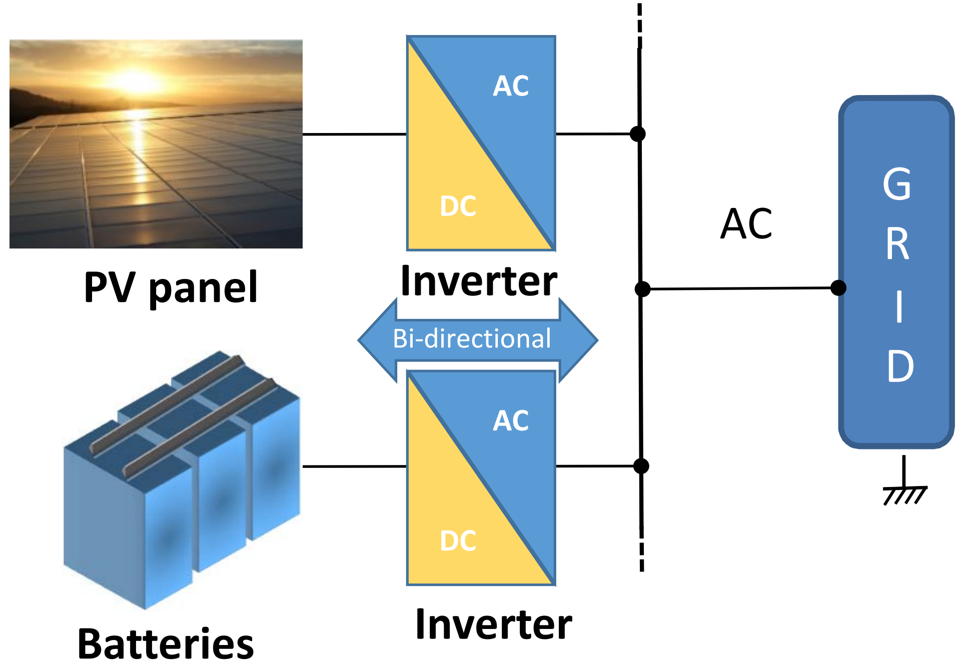
- Advantages
  - Required no additional investment
  - Easy retrofit
- Disadvantages
  - Control and stability are more difficult
  - Region dependent
    - 200-230V 50Hz
    - 120/240V 60 Hz US

Basic DC and AC Nanogrids: Solar and Energy Storage

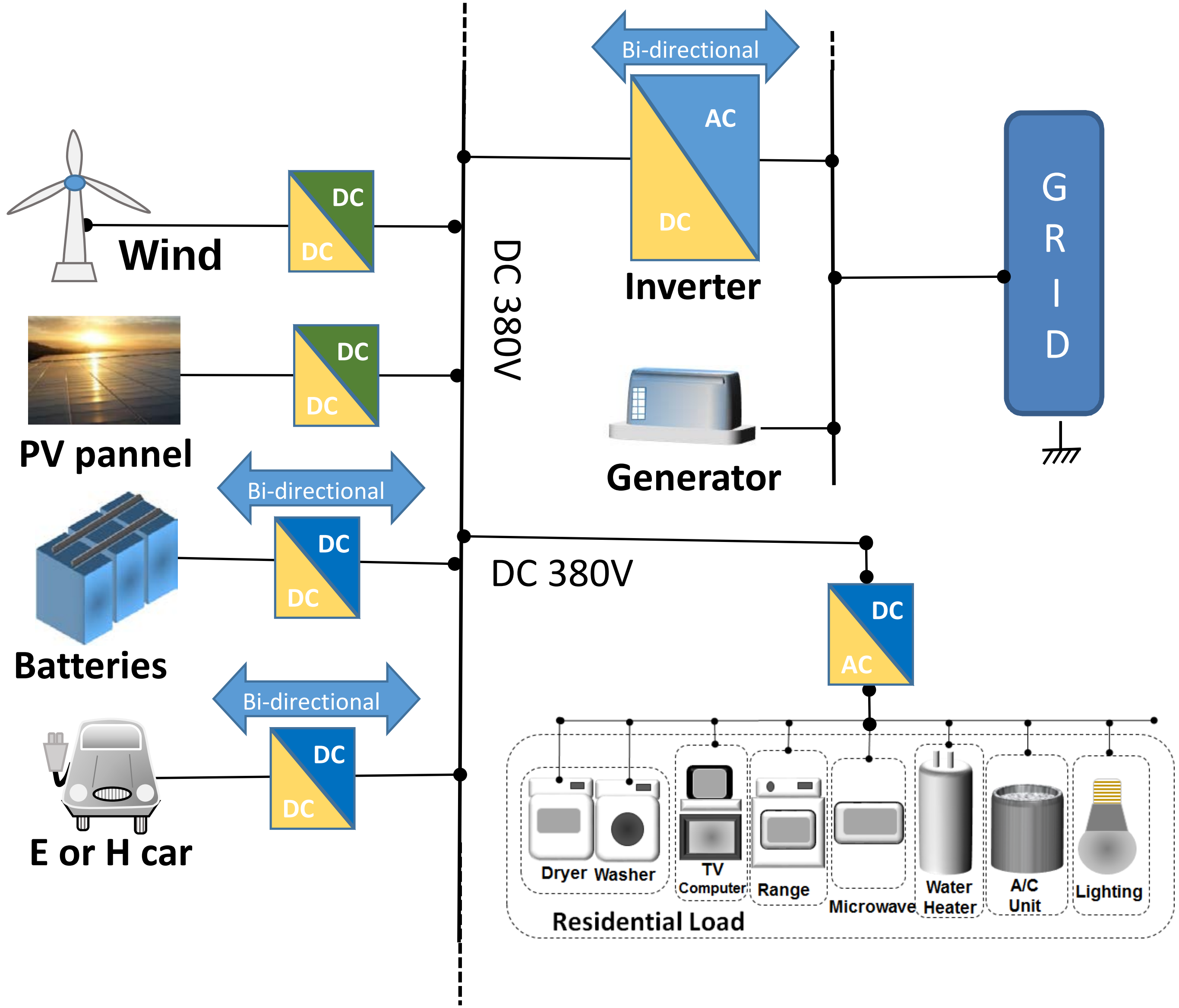
DC Nanogrid



AC Nanogrid

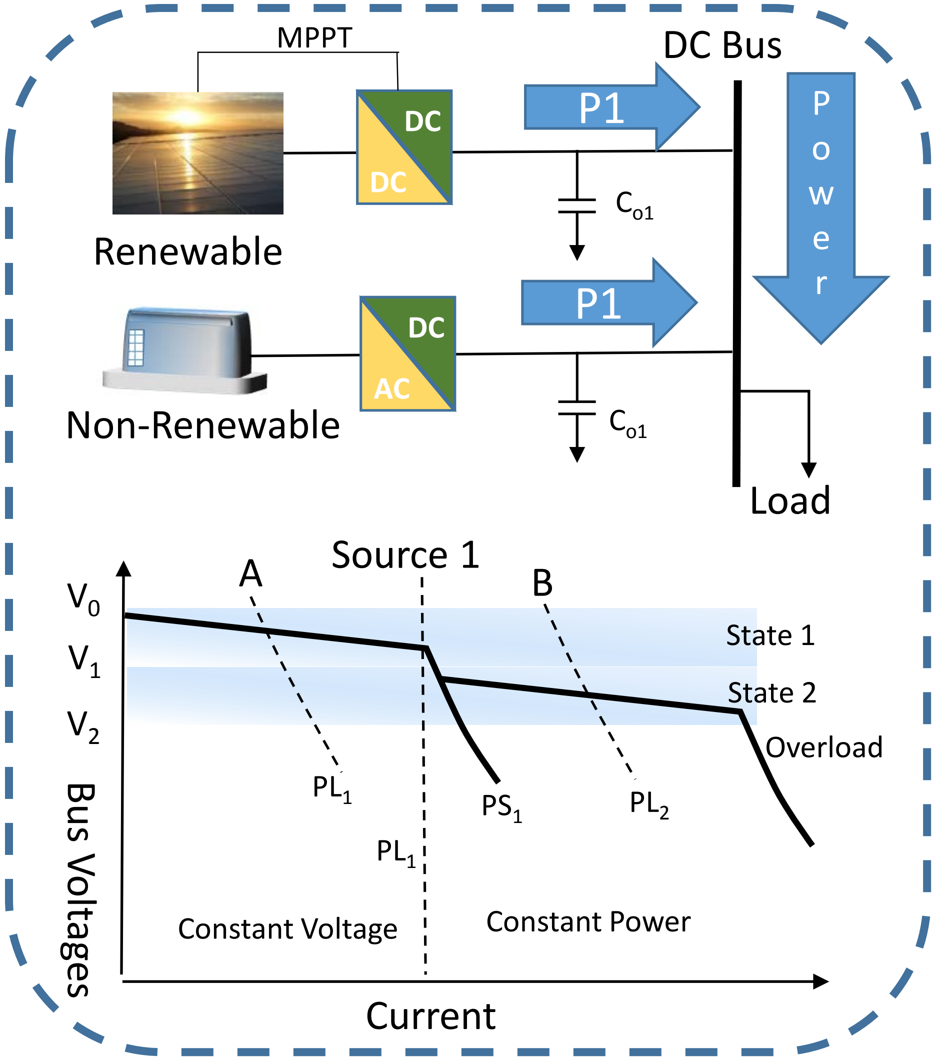


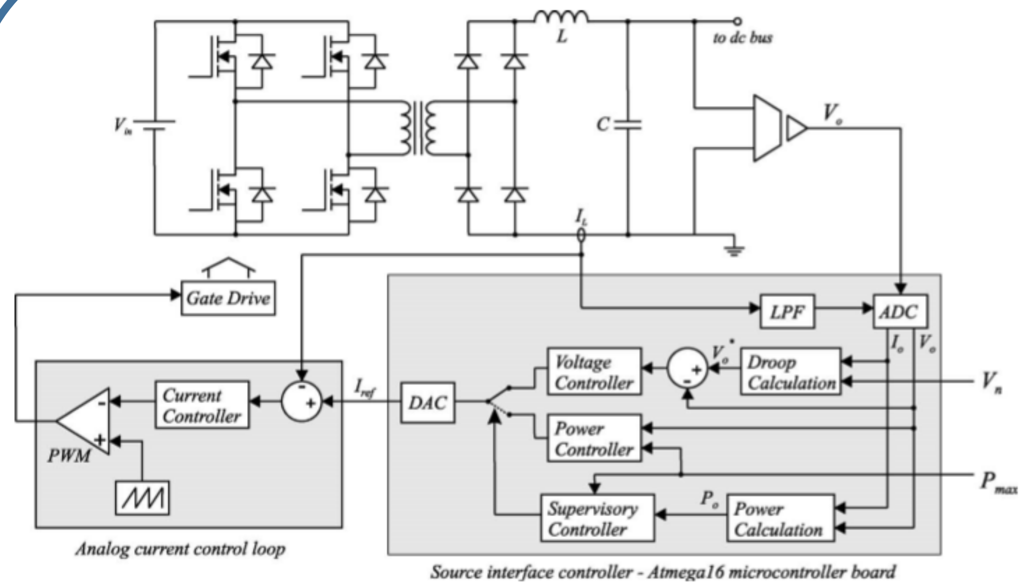
DC Residential Nanogrid



DC Residential Nanogrid- Control

Droop Voltage Control

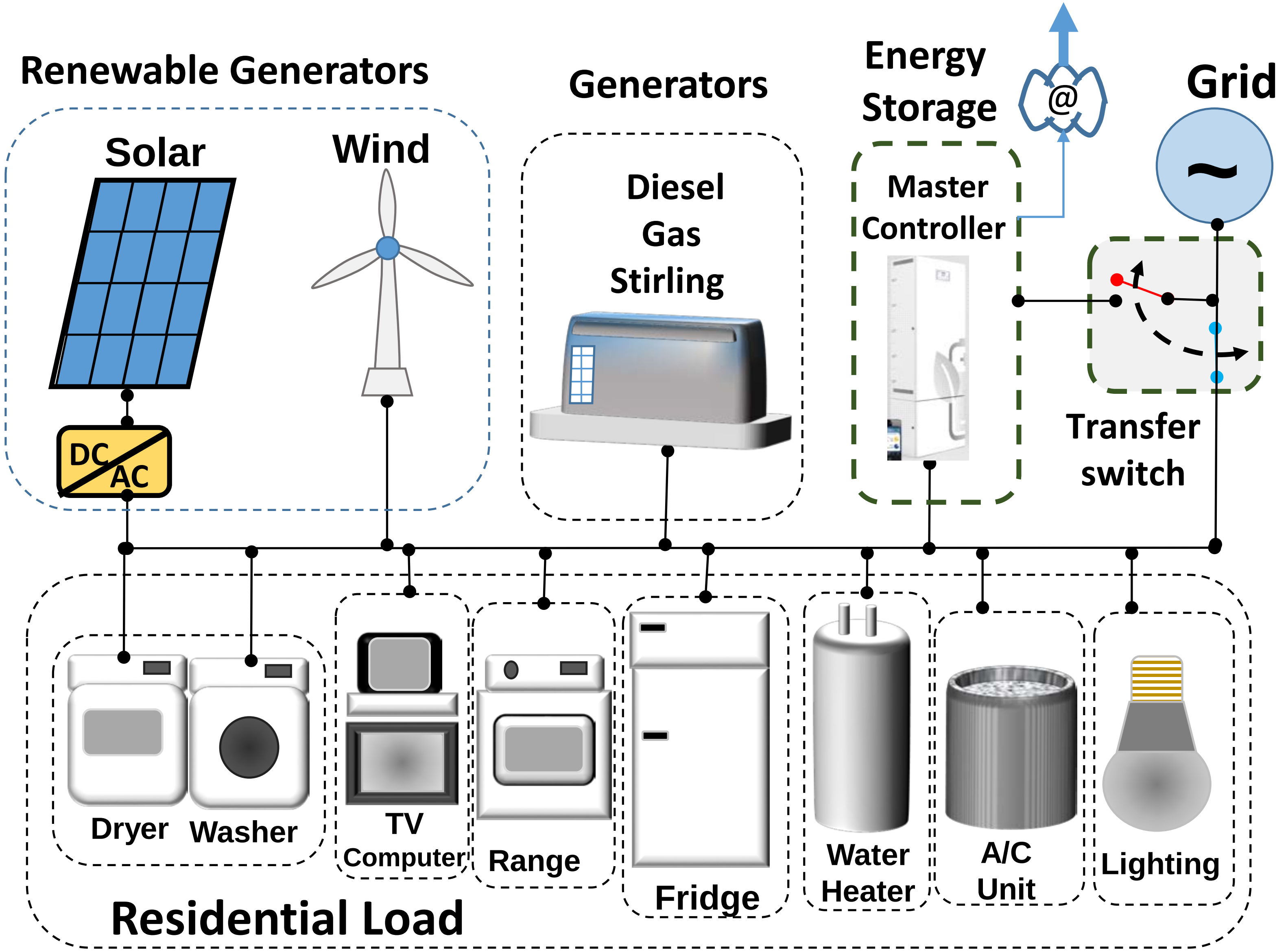




Control Example

Schönberger, J., Duke, R. and Round, S.D., 2006. DC-bus signaling: A distributed control strategy for a hybrid renewable nanogrid. *Industrial Electronics, IEEE Transactions on*, *53*(5), pp.1453-1460.

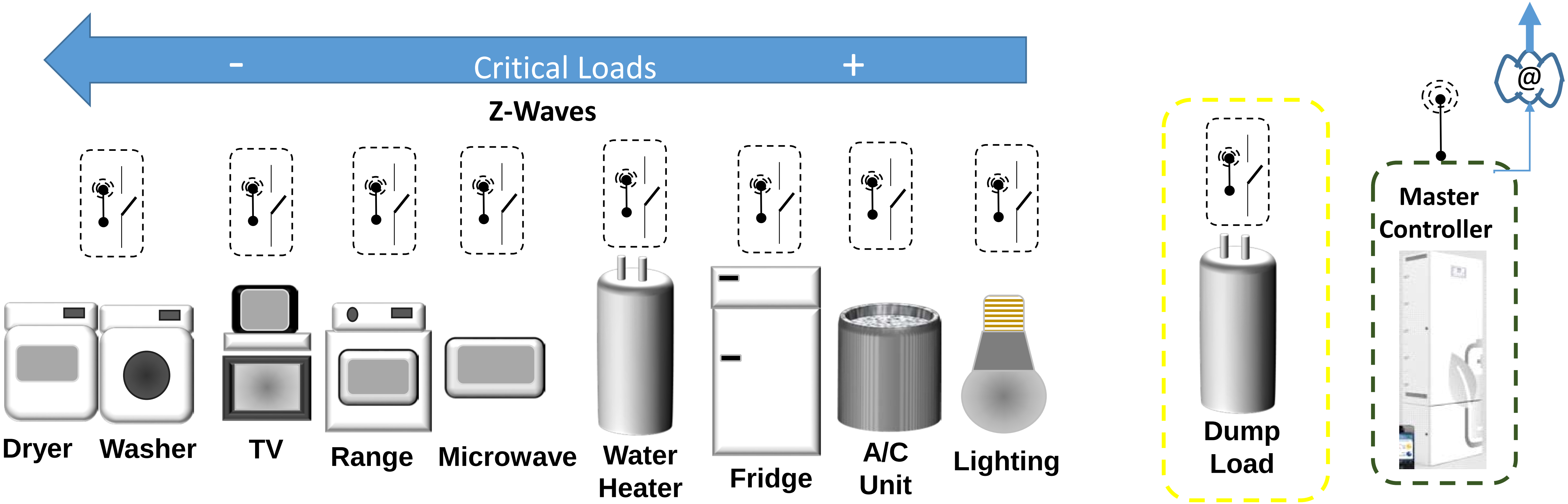
AC Residential Nanogrid



Control

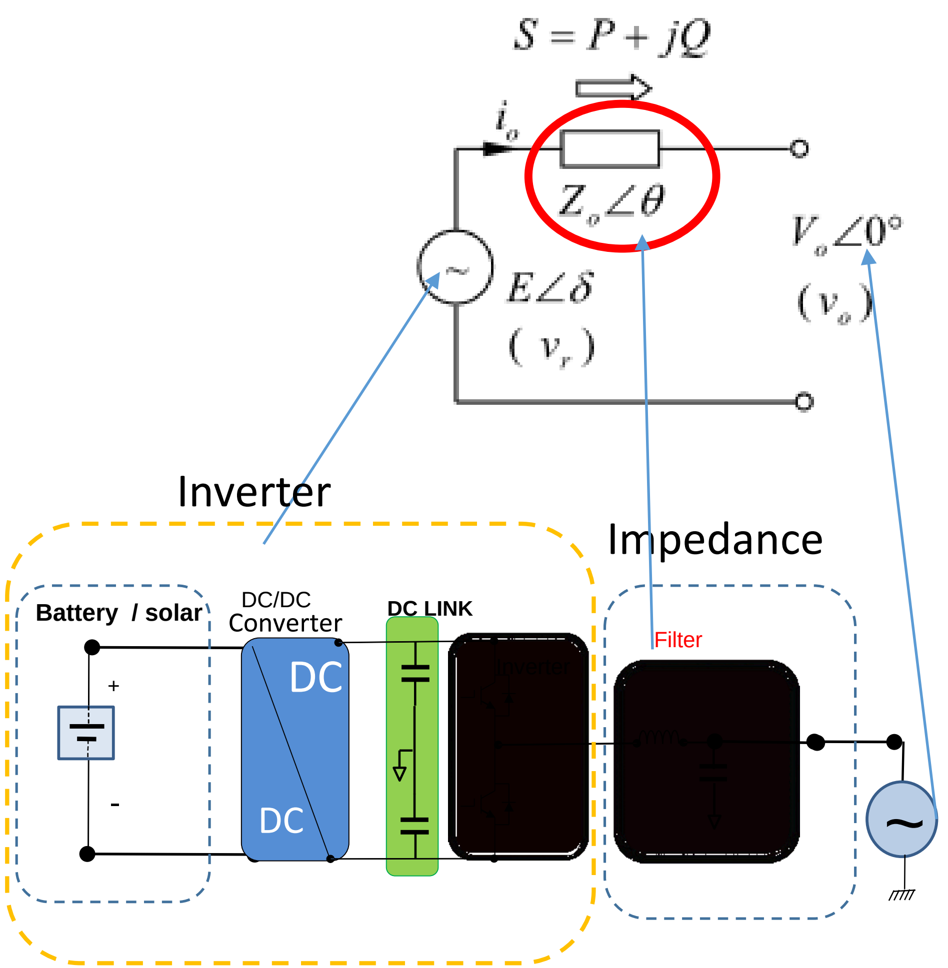
- ❑ Droop Control
- ❑ Voltages and Frequency

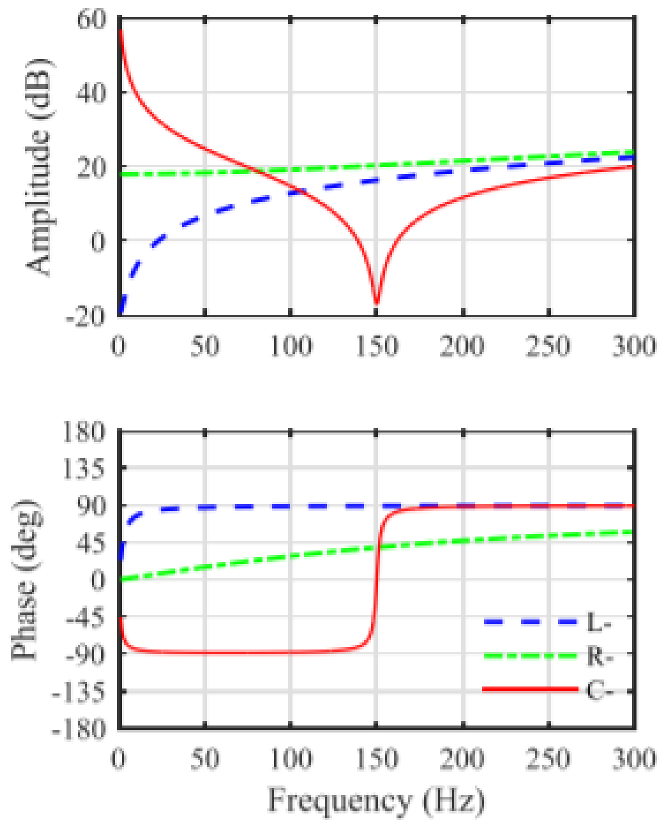
Load Handling and Criticality



Residential Load

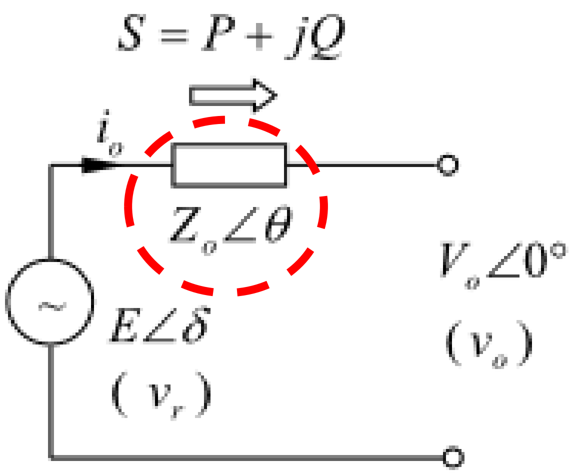
Droop AC control (Inverter)

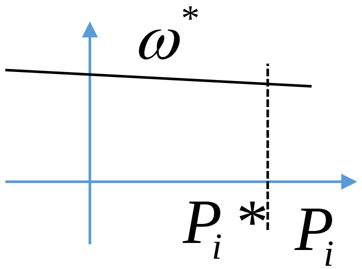




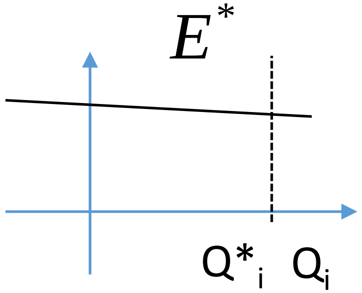
The Bode plots of the output impedance of Inverters
L-inverter (with L = 7 mH, R = 0.1**Q**, and C_o = 0 **μ**F)
R-inverter (with L = 7 mH, R = 8**Q**, and Co = 0 **μ**F)
C-inverter (with L = 7 mH, R = 0.1**Q**, and Co = 161 **μ**F).

Droop AC control





$$\omega_i \sim \omega^* - n_i P_i$$



$$E_i \sim E^* - n_i Q_i$$

$$P = \left(\frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o}\right)\cos\theta + \frac{EV_o}{Z_o}\sin\delta\sin\theta,$$

$$Q = \left(\frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o}\right)\sin\theta - \frac{EV_o}{Z_o}\sin\delta\cos\theta.$$

Assuming δ~0 and Inductive $\frac{\pi}{2}$

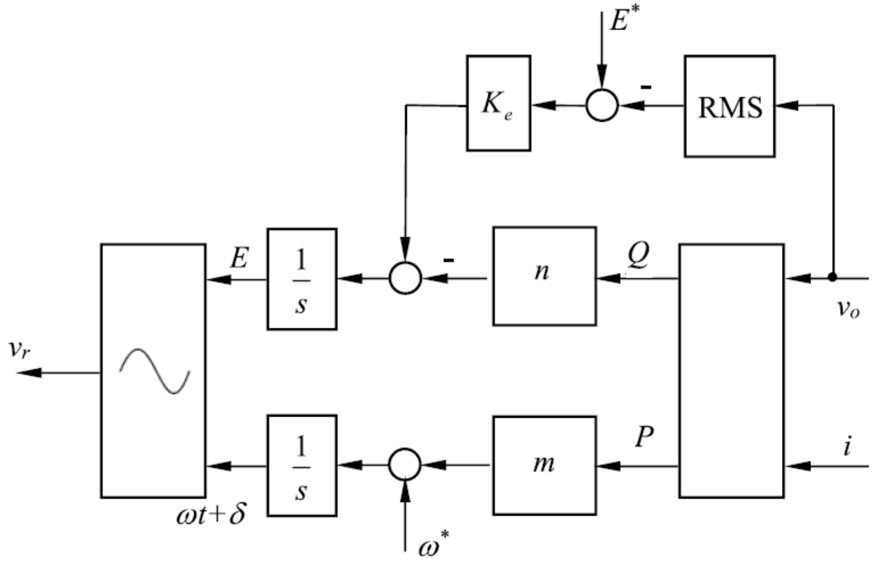
$$P \sim \frac{EV_0}{Z_0}\delta \qquad Q \sim \frac{EV_0}{Z_0} - \frac{V_0^2}{Z_0}$$

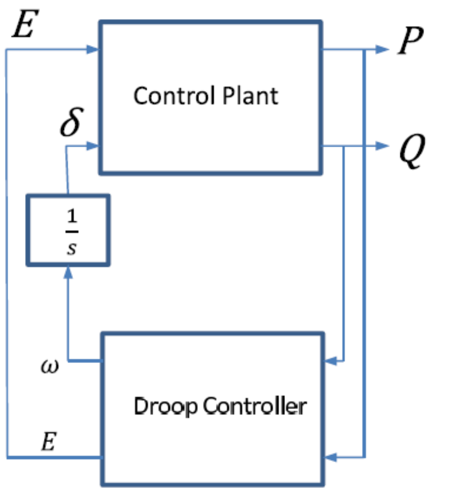
$$P \sim \delta \qquad Q \sim E$$

Universal Droop Control of Inverters

Droop controllers for L-, R-, C-, RL-, and RC-inverters.

Inverter type	θ	Input-output/Droop relationship	Droop controller
L-	$\frac{\pi}{2}$	$P \sim \delta$	$E = E^* - nQ$
		$Q \sim E$	$\omega = \omega^* - mP$
R-	0°	$P \sim E$	$E = E^* - nP$
		$Q \sim -\delta$	$\omega = \omega^* + mQ$
C-	$-\frac{\pi}{2}$	$P \sim -\delta$	$E = E^* + nQ$
		$Q \sim -E$	$\omega = \omega^* + mP$
R_C-	$(-\frac{\pi}{2}, 0)$	Coupled	Depends on θ
R_L-	$(0, \frac{\pi}{2})$	Coupled	Depends on θ





Zhong, Qing-Chang, and Yu Zeng. "Universal Droop Control of Inverters with Different Types of Output Impedance."

Fundamentals
Back up battery storage

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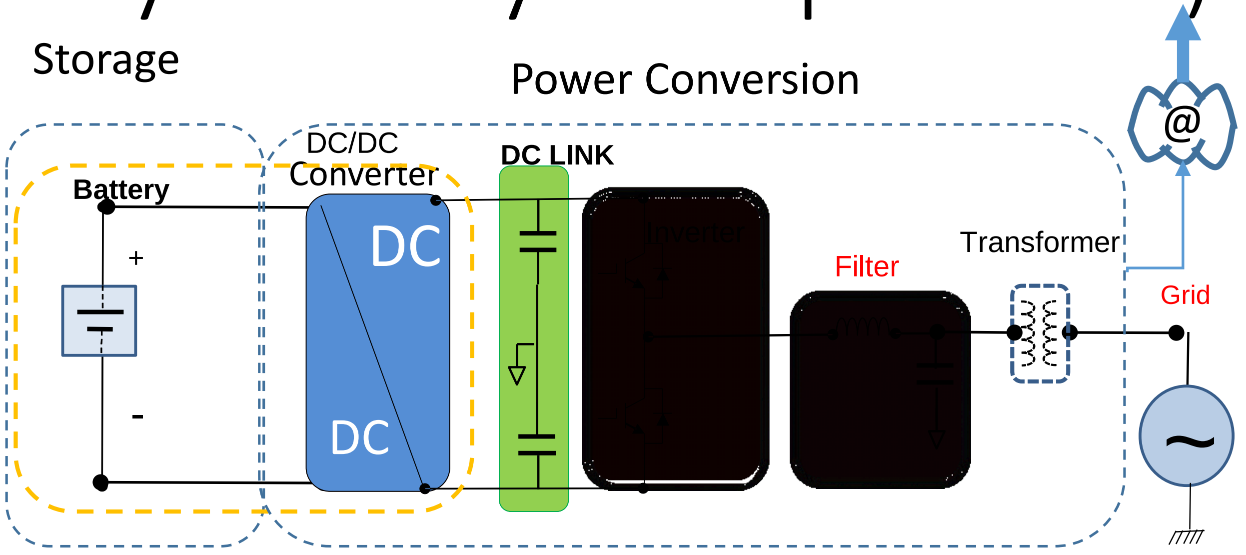
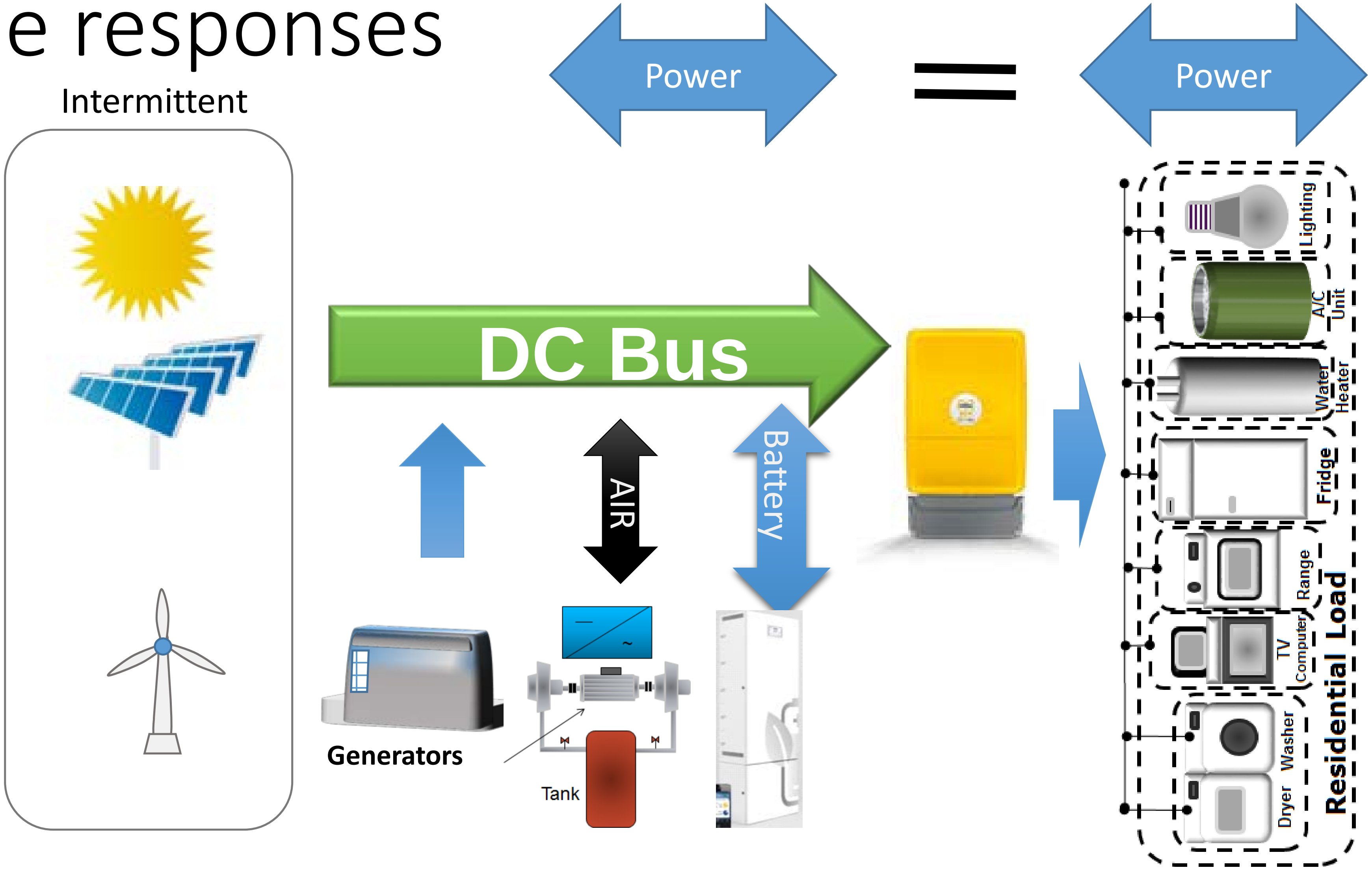
Energy Storage (Why Battery & Capacitor?)

- ❑Air Compressor
- ❑Hydraulics
- ❑Thermal (Molten Salt)
- ❑Inertia Wheels
- ❑Magnetics
- ❑Capacitor (Super)
- ❑Battery
- ❑Flow Batteries



- ❑Dynamic Power Compensation (very fast – few milliseconds)
- ❑Sized according its nanogrid
- ❑Able to regulate the nanogrid
- ❑Weather prediction via internet

Time responses



Fast Energy Storage

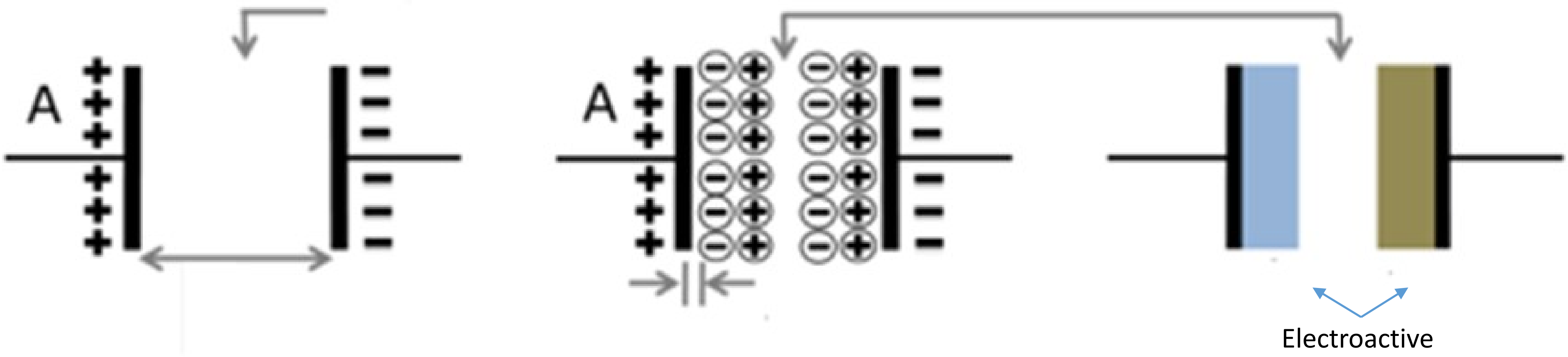
Electrolytic capacitor

Dielectric

Ultra-capacitor

Electrolyte

Battery



Electroactive material

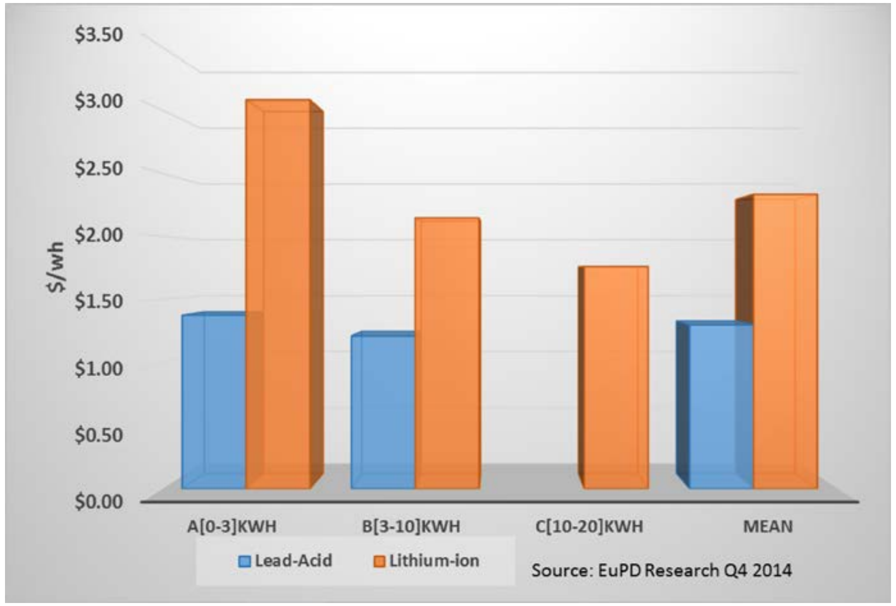
- 1000M cycles
- 95-98% charge efficiency
- -40 to 85 ^{o}C

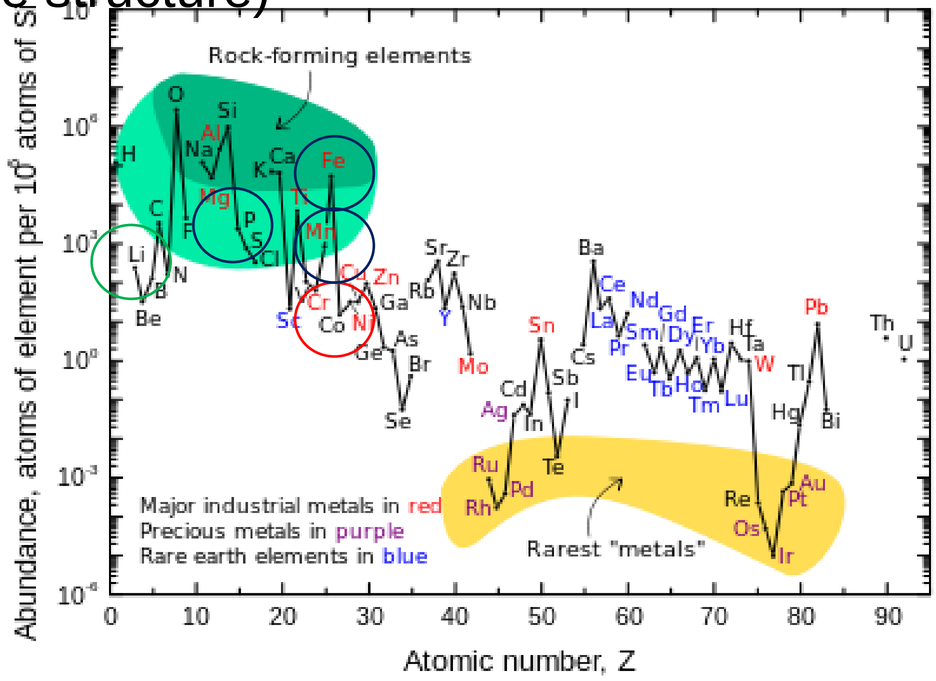
- 1M cycles
- 99% charge efficiency
- -40 to 85 ^{o}C

- 10000 cycles
- 85-99% charge efficiency
- -10 to 60 ^{o}C

Batteries: State-of-the-Art

- Lead Acid
- Nickel–Cadmium
- Lithium-ion
  - Lithium cobalt oxide LiCoO2 (metal oxide)
  - Lithium manganese oxide LiMn2O4 (tunneled structure)
  - Lithium iron-phosphate LiFePO4 (olivine structure)





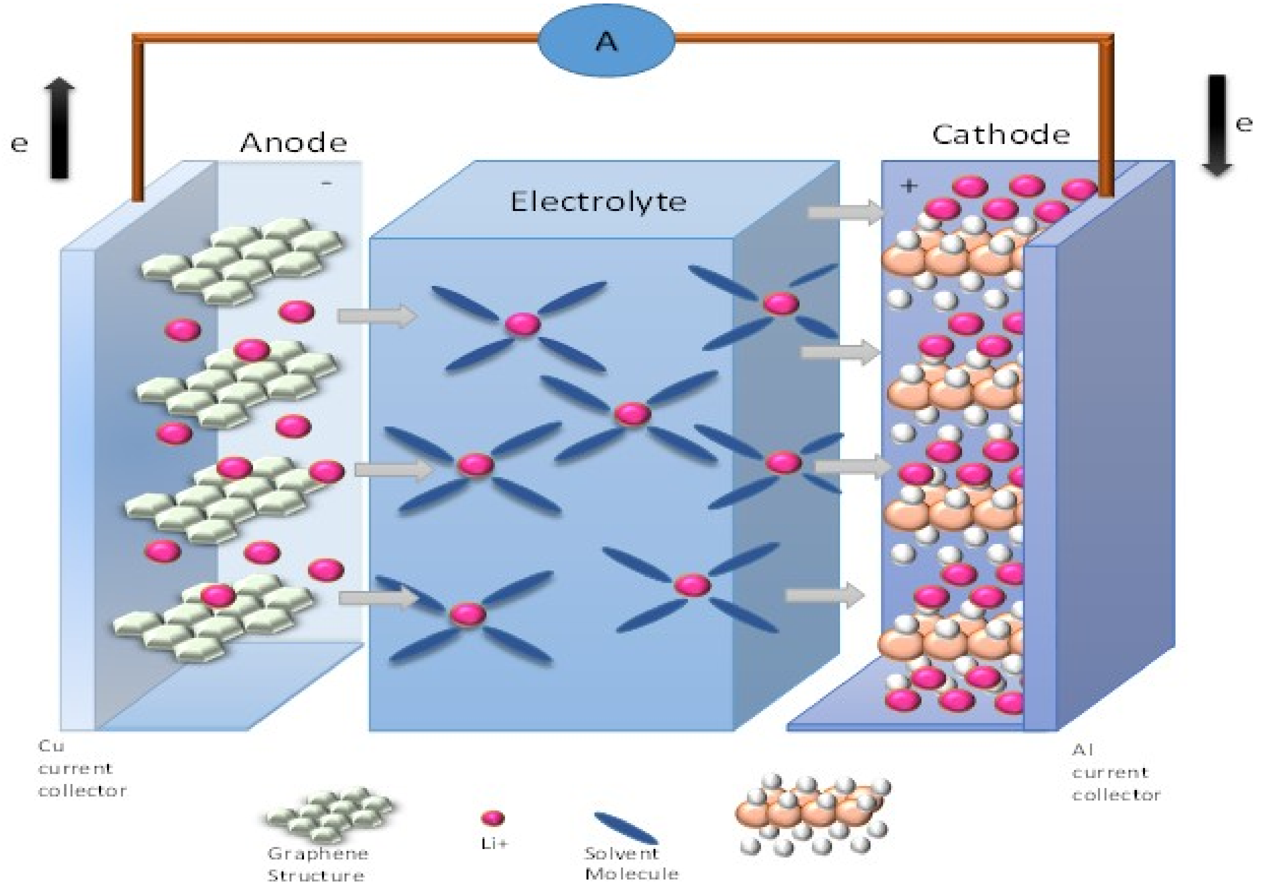
IOXUS super capacitor

<table>
<tr><td colspan="6">2.70V Cylindrical cells (-40°C to +85°C)
2.85V Cylindrical cells (-40°C to +65°C)
2.70V Pouch cells (-20°C to +65°C)</td><td rowspan="3">• High energy density
• High power density
• Low ESR
• 1M cycles
• Multiple patents</td></tr>
<tr><td>Cylindrical</td><td>100F</td><td>385F</td><td>1250F</td><td>2000F</td><td>3000F</td></tr>
<tr><td>Pouch</td><td>160F
210F</td><td>445F</td><td>600F</td><td>1245F</td><td>1600F</td></tr>
</table>

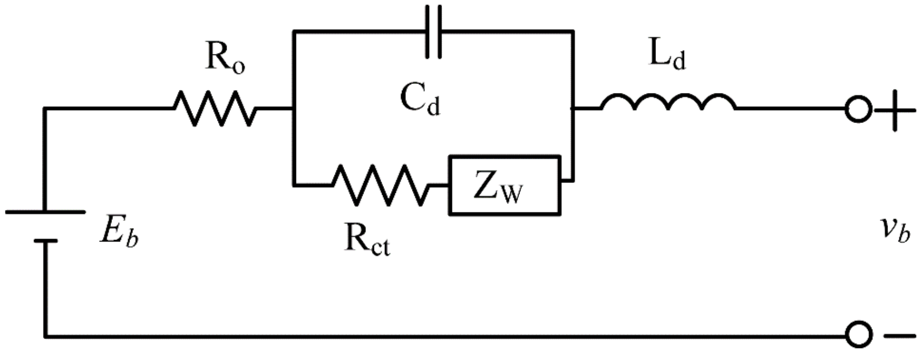
Batteries

- Basic structure
  - Battery cell
  - Cell arrangements
  - Balancing circuits
- Modeling
- Life and modeling
  - Cycles
  - Current dependence
  - Temperature dependence

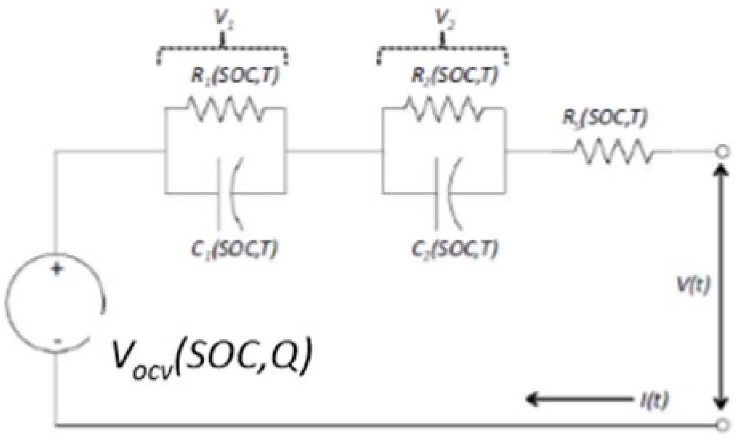
- Positive electrode
- Negative electrode (carbon-graphite)
- Electrolyte and separator



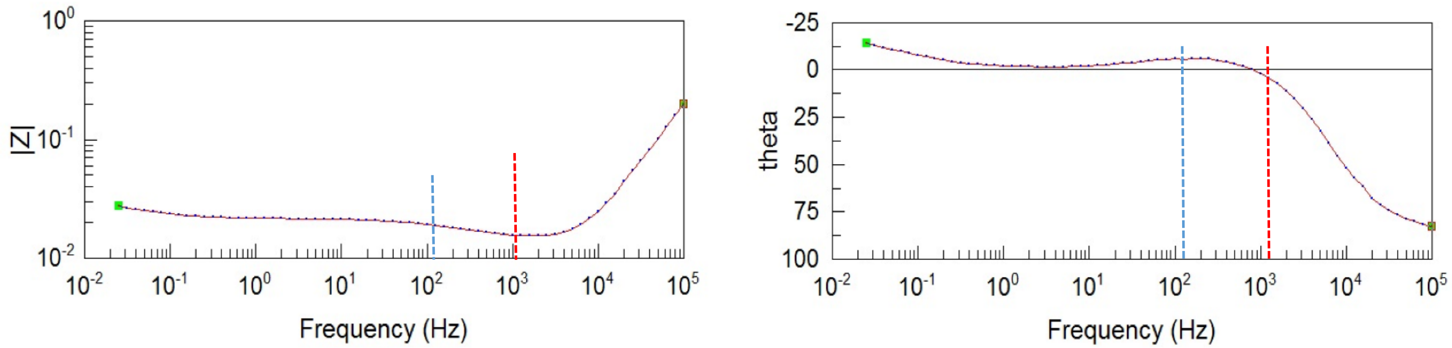
Modeling



R_o
C_d
L_d
Z_W
R_{ct}
E_b
v_b



V_1
V_2
$R_1(SOC,T)$
$R_2(SOC,T)$
$R_0(SOC,T)$
$C_1(SOC,T)$
$C_2(SOC,T)$
$V(t)$
$I(t)$
$V_{ocv}(SOC,Q)$

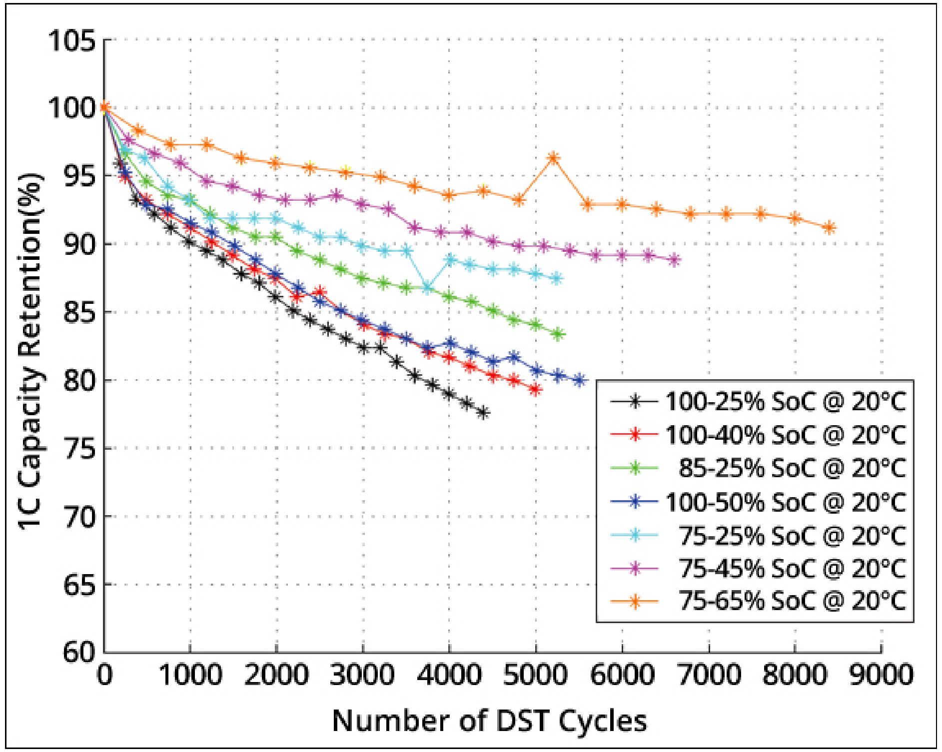


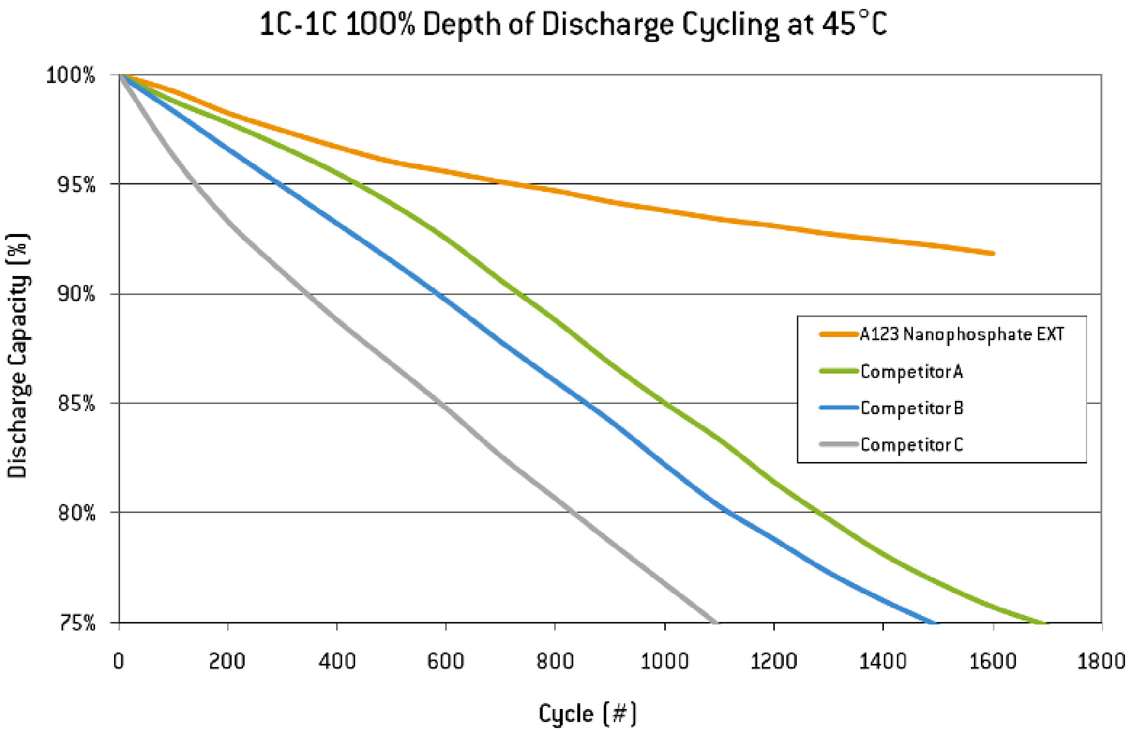
|Z|
Frequency (Hz)
theta
Frequency (Hz)

(a) (b)

Life Model- Charge capacitace

Capacity loss as a function of charge and discharge bandwidth.

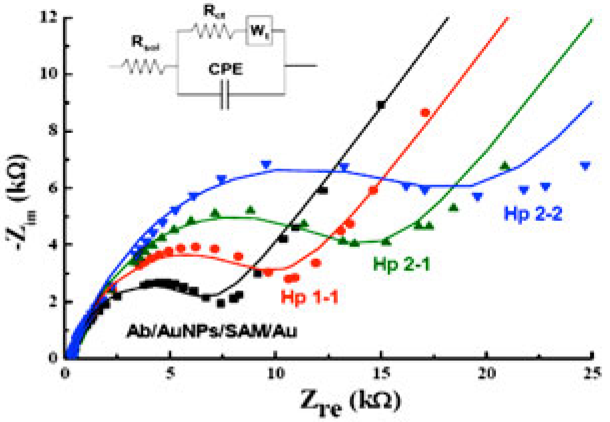


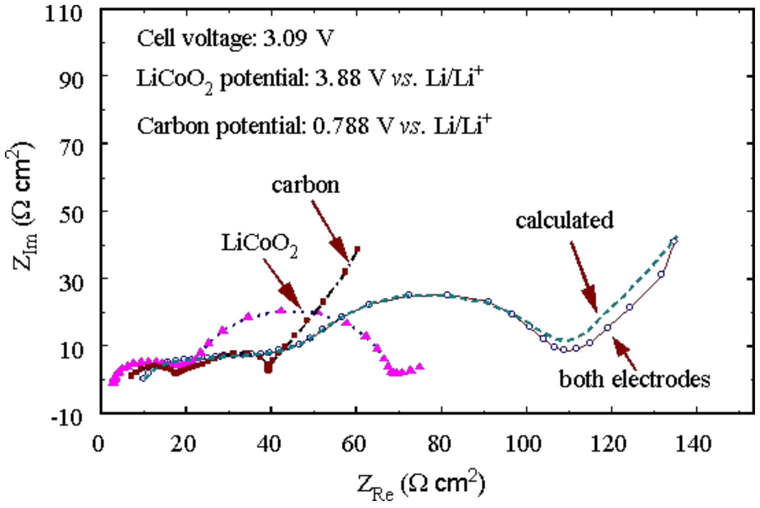


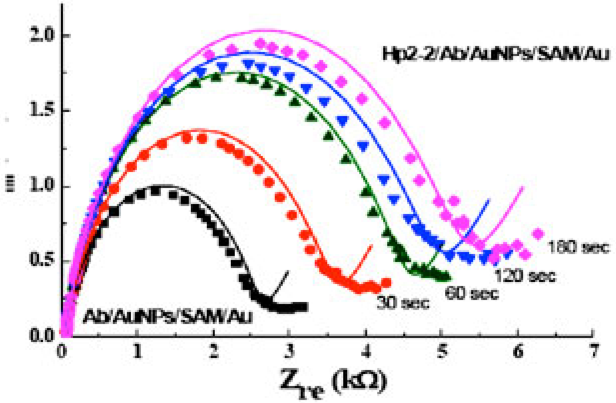
[Nissan Leaf case]

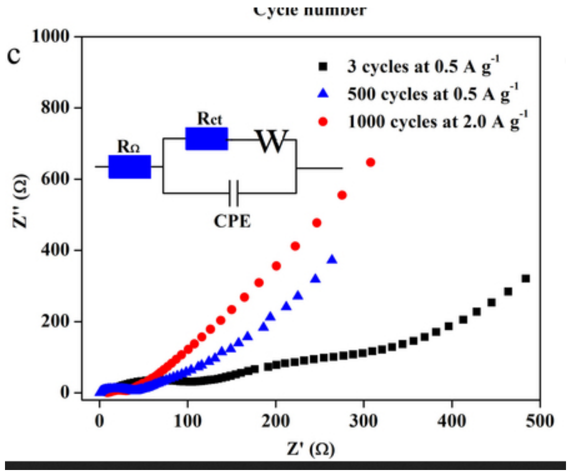
https://www.nrel.gov/docs/fy13osti/58550.pdf

Life model _Impedance Real Part and Aging



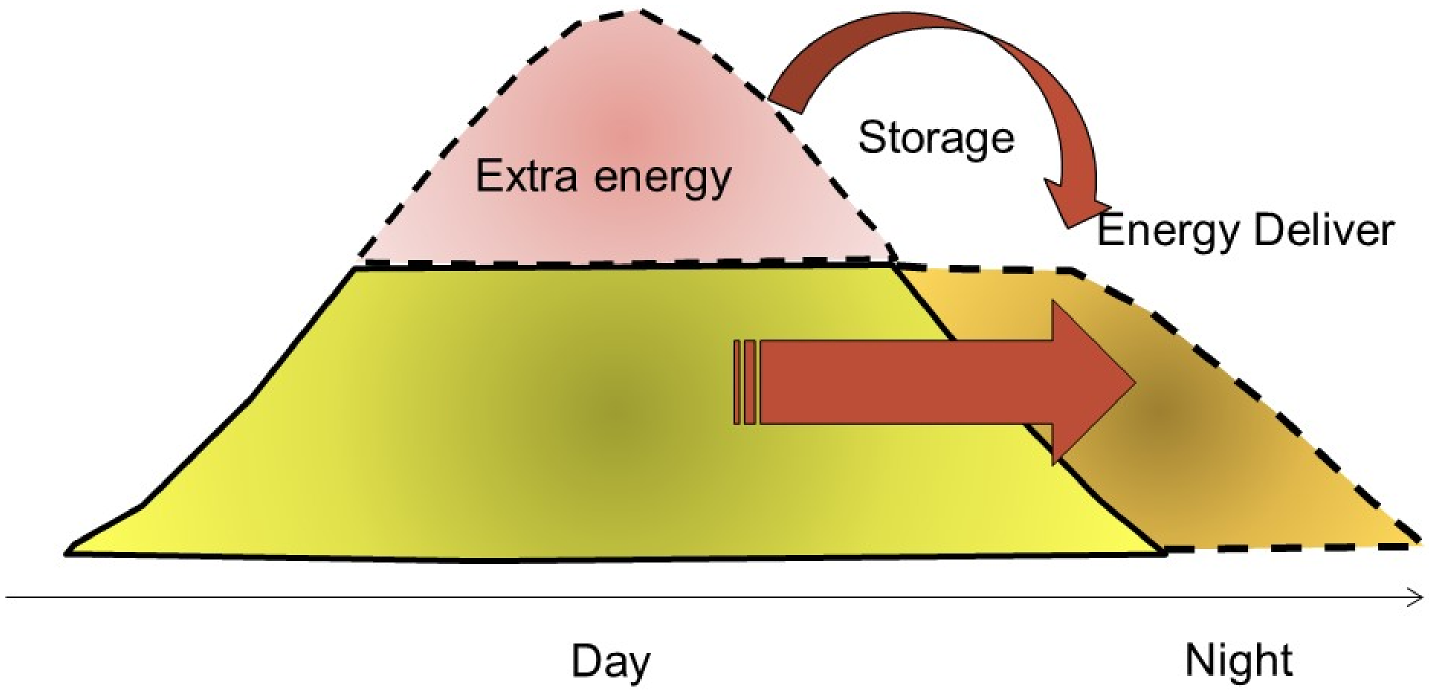






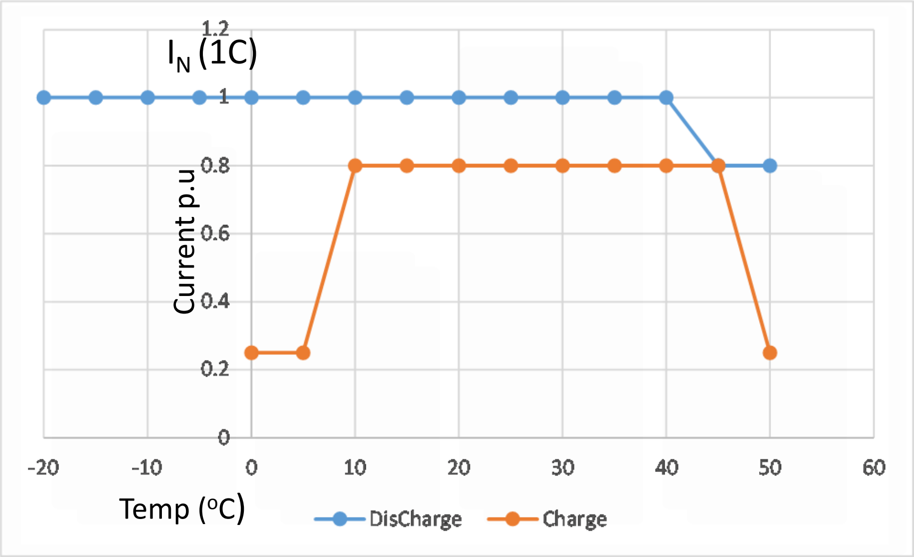
Battery dimensioning
Charge and discharge

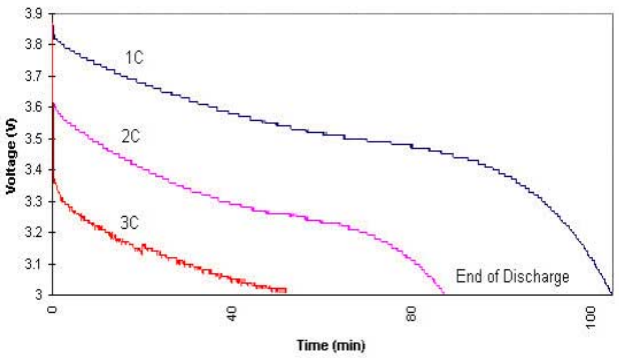
Solar –storage relation



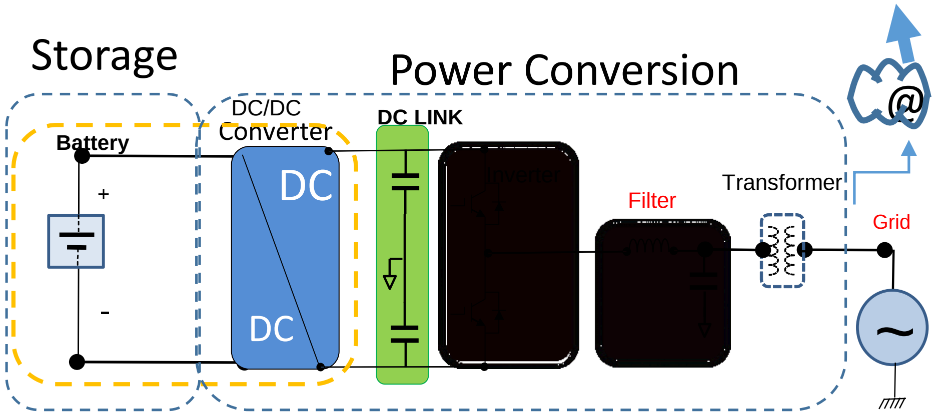
Peak demand (other aspect)

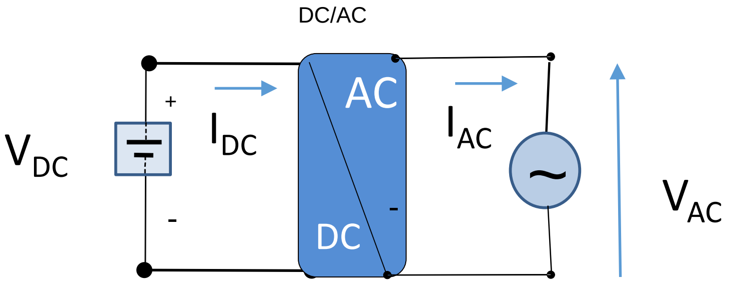
Battery Spec Temperature Charge and Discharge





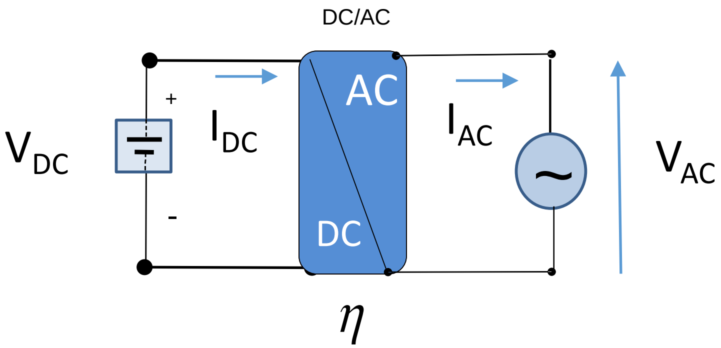
$$SOC = \int_{V1}^{V2} I(t)dt$$



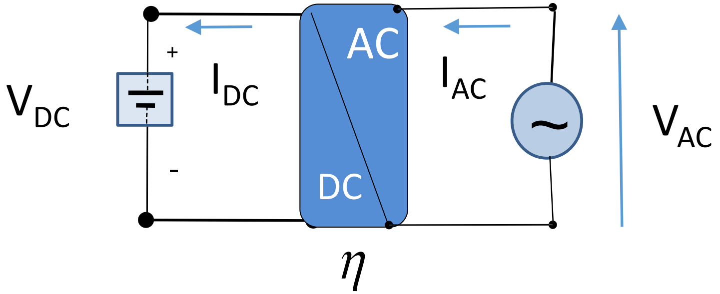


Battery Specs Temperature Charge and Discharge Energy storage

$I_{DC\_DISCHARGE}$=1.0 P.U



I_{DC_CHARGE} = 0.8 P.U



$$P_{DC} = I_{DC} . V_{DC} = \eta \cdot I_{RMS} . V_{RMS} = P_{AC}$$

I_{DC_CHARGE} = η $I_{DC\_DISCHARGE}$

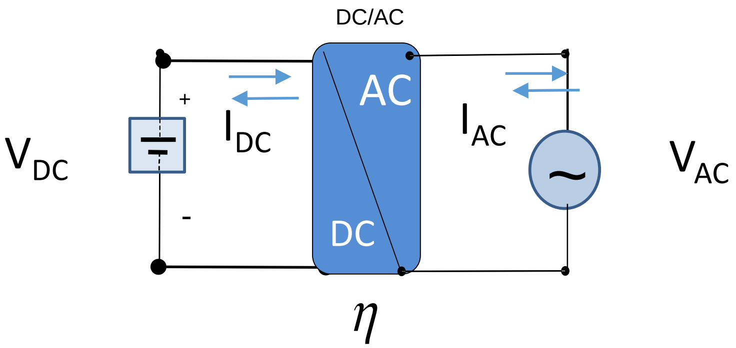
η >0.8

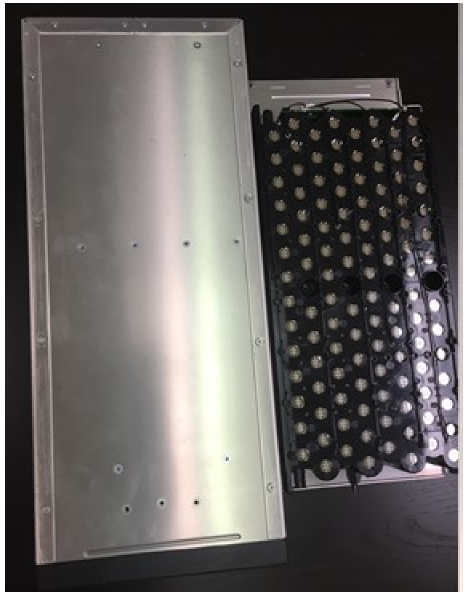
Energy and Power Arrangement

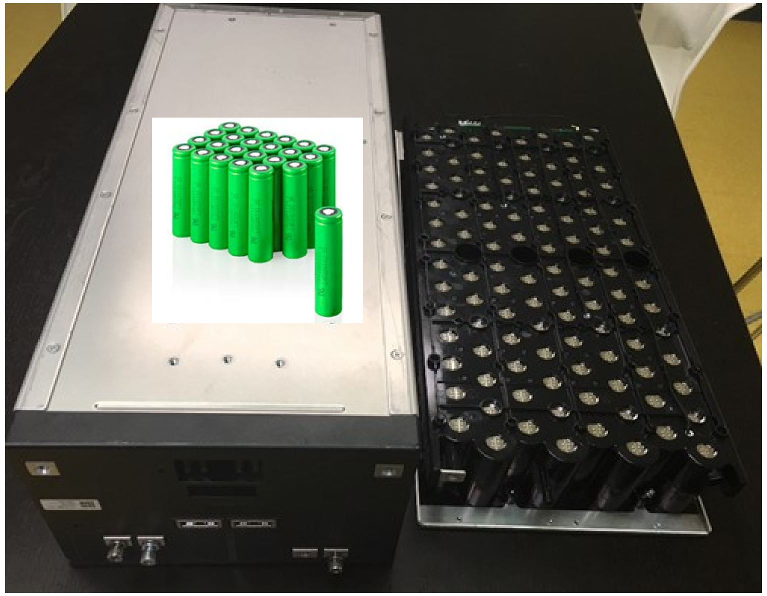
3 ampere-hours, 3.2 V 14x16

Energy = kW/h

Power= kW







Battery system in a nanogrid go from 4kw/h to 16 kW/h

Inverters Fundamentals

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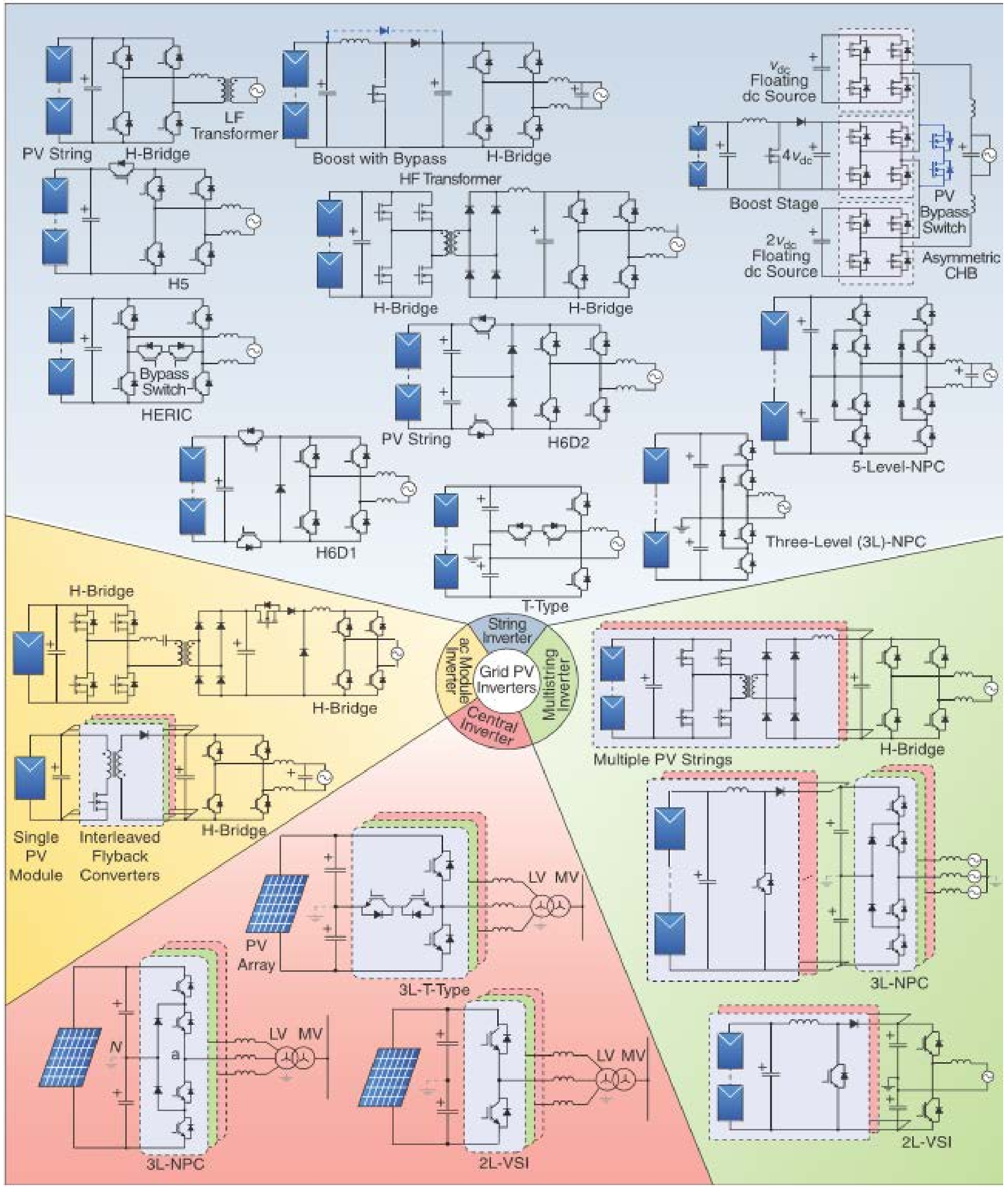
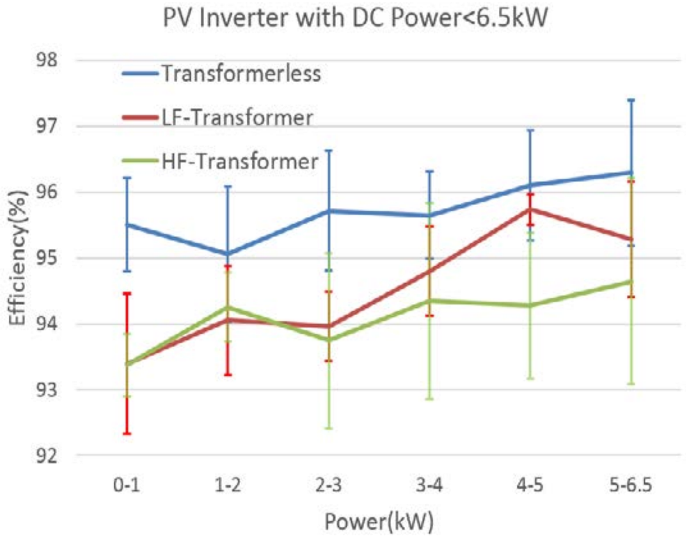
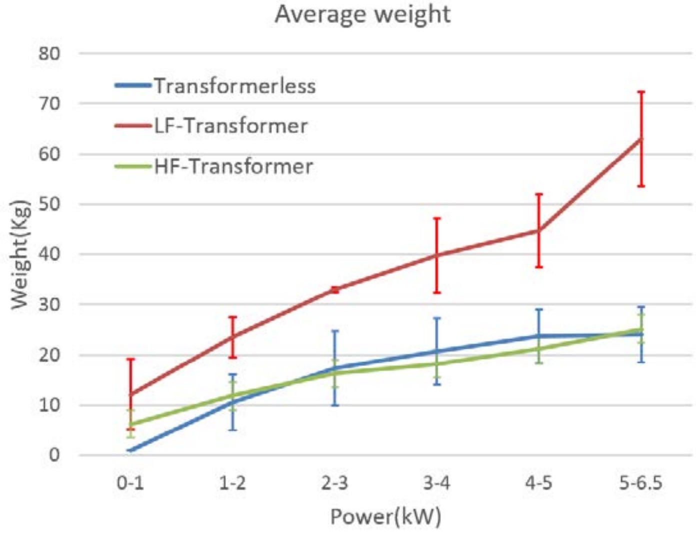
Solar Inverter Evolution



- ❑ LF- Transformer
- ❑ HF-Transformer
- ❑ Transformerless
  - ❑ Safety
  - ❑ Parasitic current





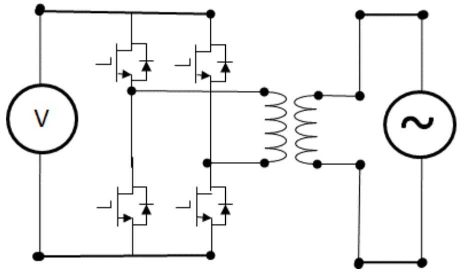
* Kouro, S. Leon, J.I. ; Vinnikov, D. ; Franquelo, L.G. "Grid-Connected Photovoltaic Systems: An Overview of Recent Research and Emerging PV Converter Technology" Industrial Electronics Magazine, IEEE Volume:9 , Issue: 1 P:47 - 61 March 2015

Bi-directional Inverter (Voltages based)

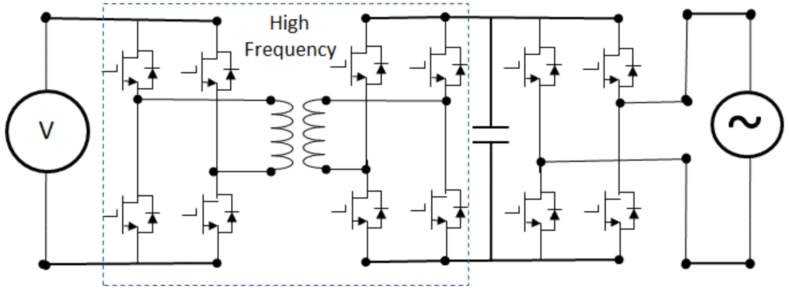
- Inverter Topology Type
  (Basic topologies and their advantages and disadvantages)
- Inverter Connection Type
  - **Low-frequency transformer:**
- The basic structure consists of one or more H-bridges Single H-bridge, high PWM
  - Center tap
  - Multiple H-bridges with interleaving
- The course contains some design examples.
  - **High-frequency transformer**
- The isolation is accomplished by high-frequency switching on the DC side using a high-frequency core, traditionally ferrite. Recent developments in low-cost and low-loss materials are challenging ferrite use.
  - Topology and Design examples, including inverter and magnetic parts
  - Use of new semiconductors GaN and SIC
  - **Transformerless**
    Eliminating the transformer reduces cost and significantly improves efficiency. This course analyzes the topologies that can achieve transformerless operation

Voltages Based Bi-directional inverter

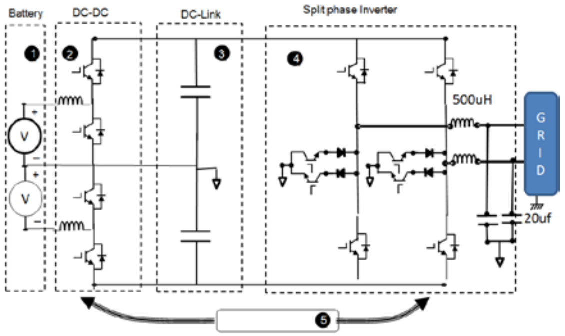
Voltage Based Inverter



- ❑ LF- Transformer (UPS)

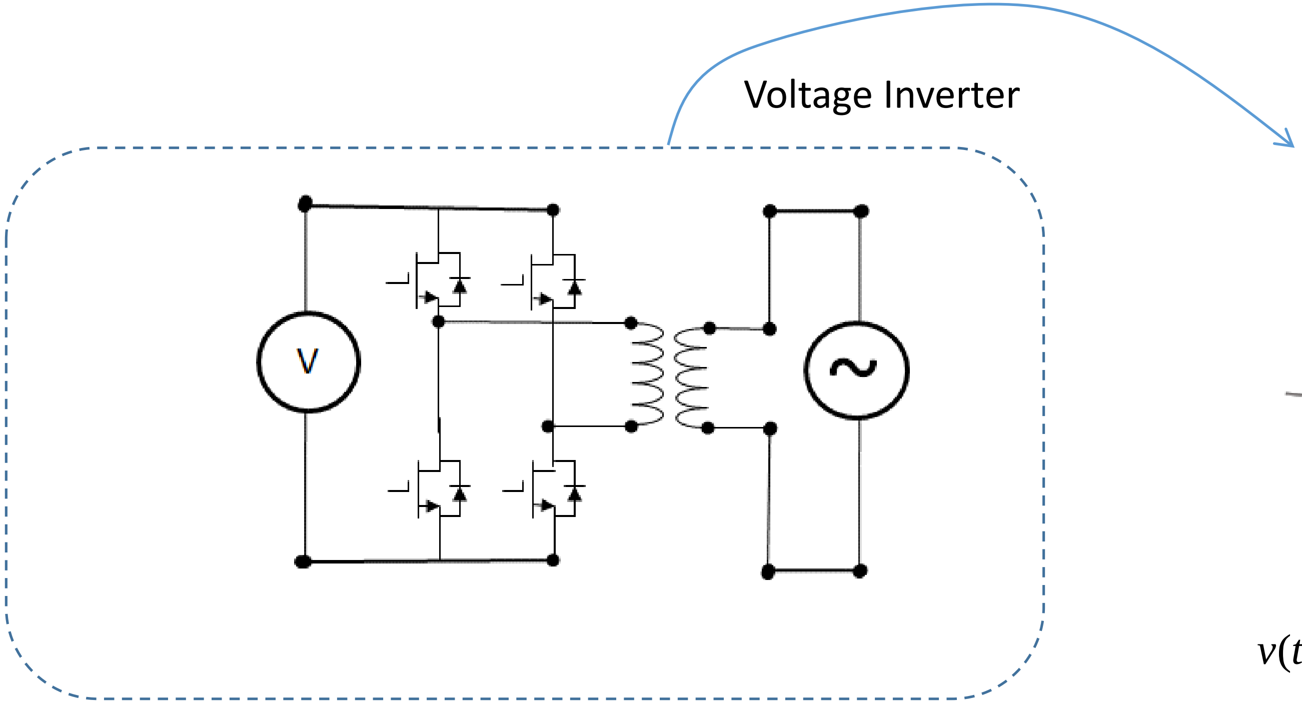


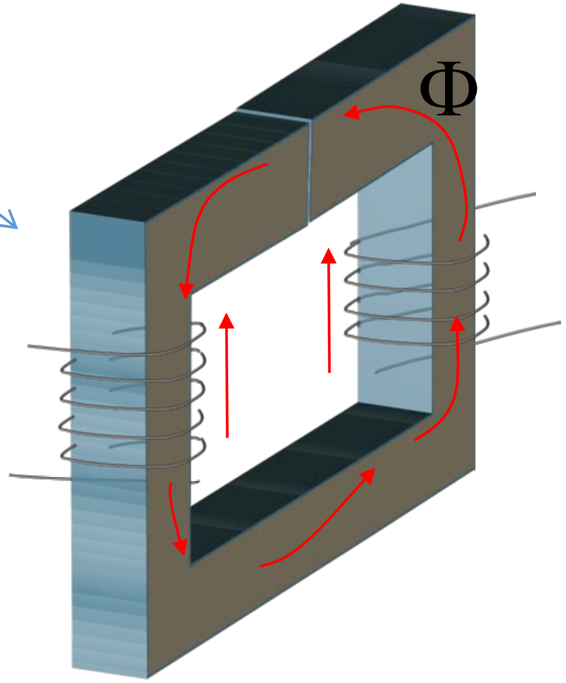
- ❑ HF-Transformer



- ❑ Transformerless

Low Frequency Bi-directional inverter

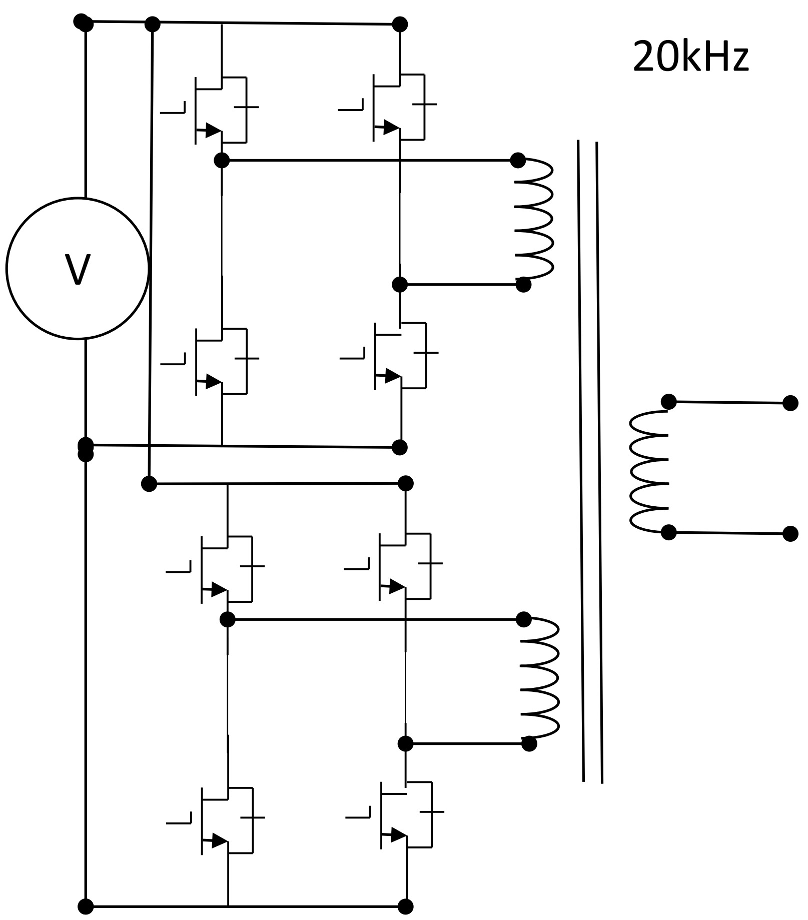


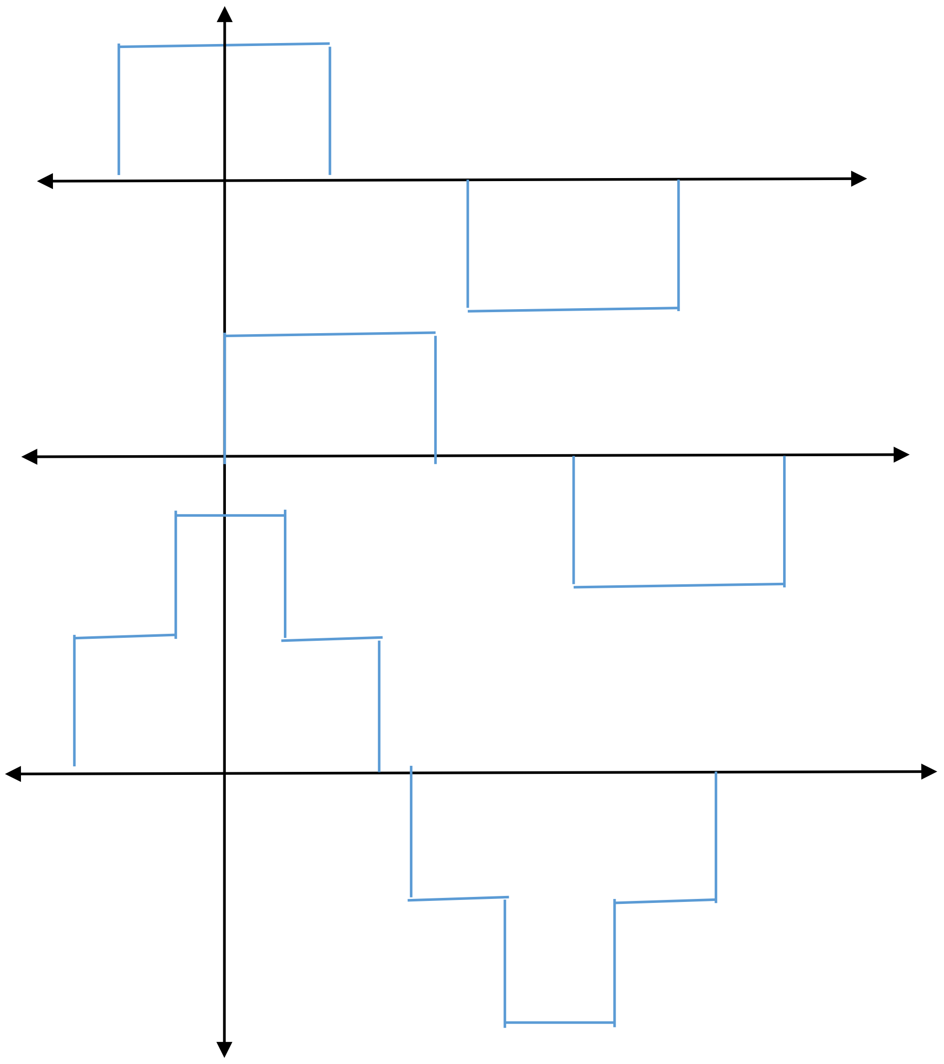


$$v(t) = -N \frac{\partial}{dt} \Phi(\omega t)$$

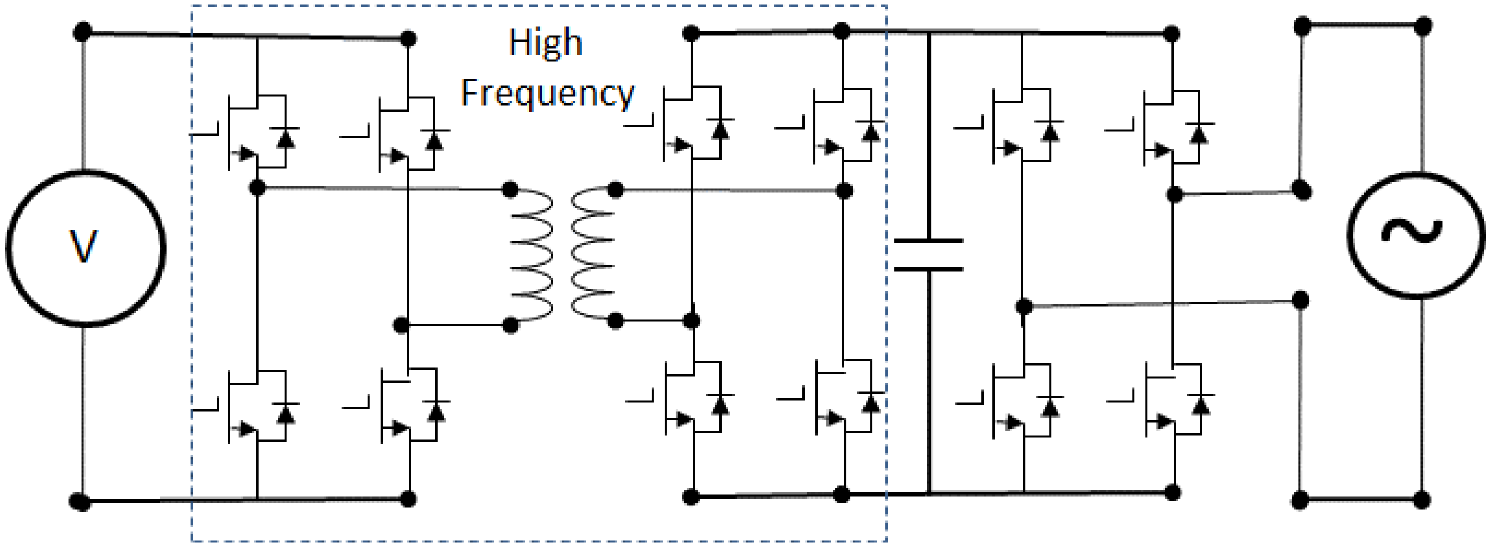
$$V_{RMS} = 4.44\, f B_{\max} A.N$$

Low Frequency Bi-directional inverter interleaving

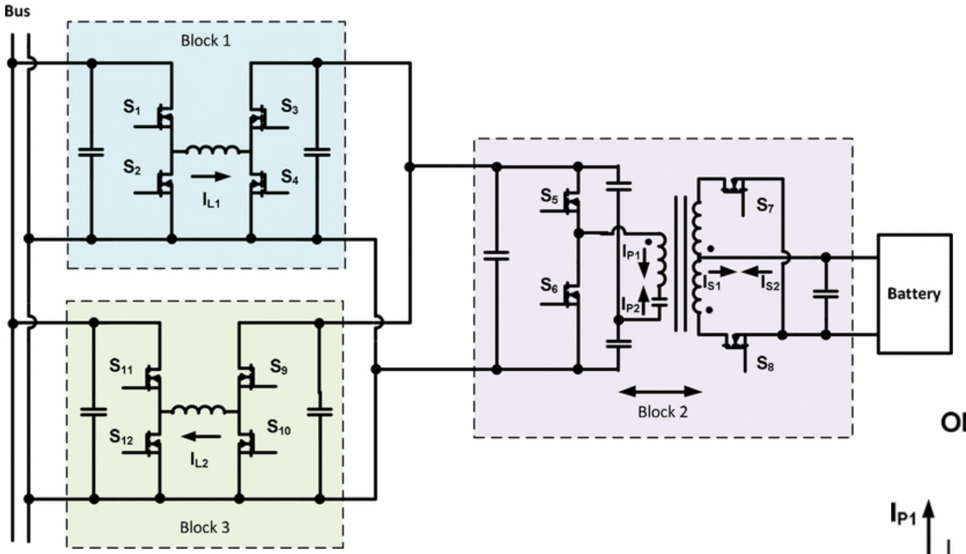


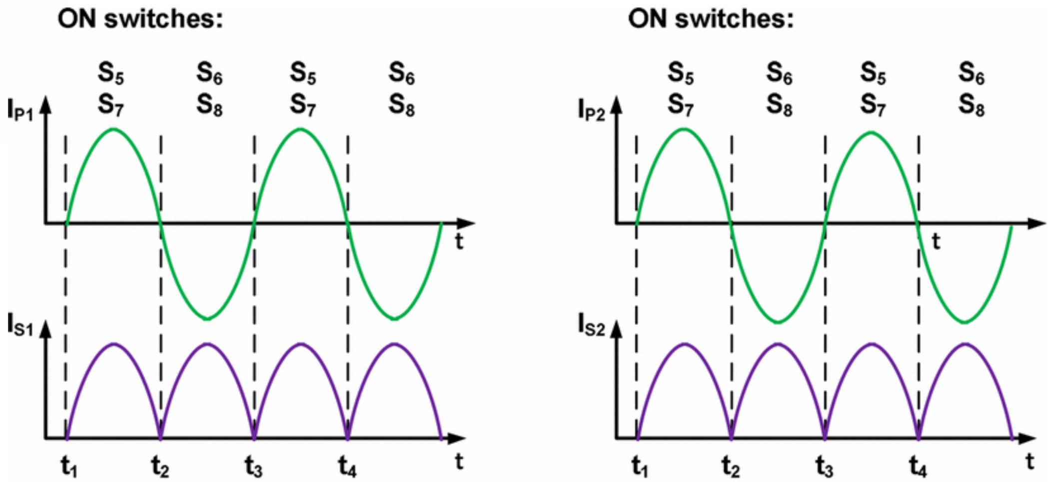


HF Inverter _Hard Switch



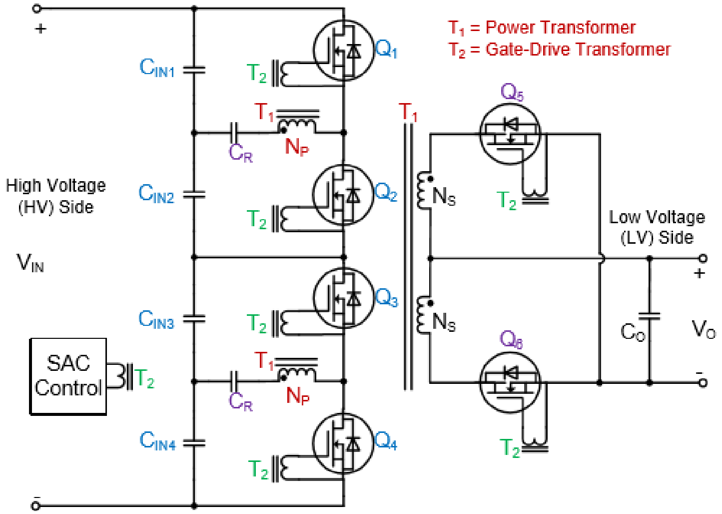
High frequency ZCS

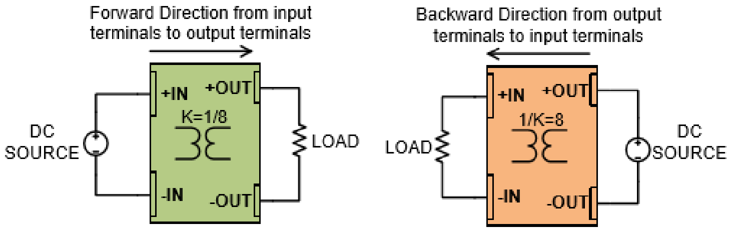




(a) (b)

Vicor solution





Xiaoyan Yu and Paul Yeaman, “A new high efficiency isolated bidirectional DC-DC converter for DC-bus and battery bank interface

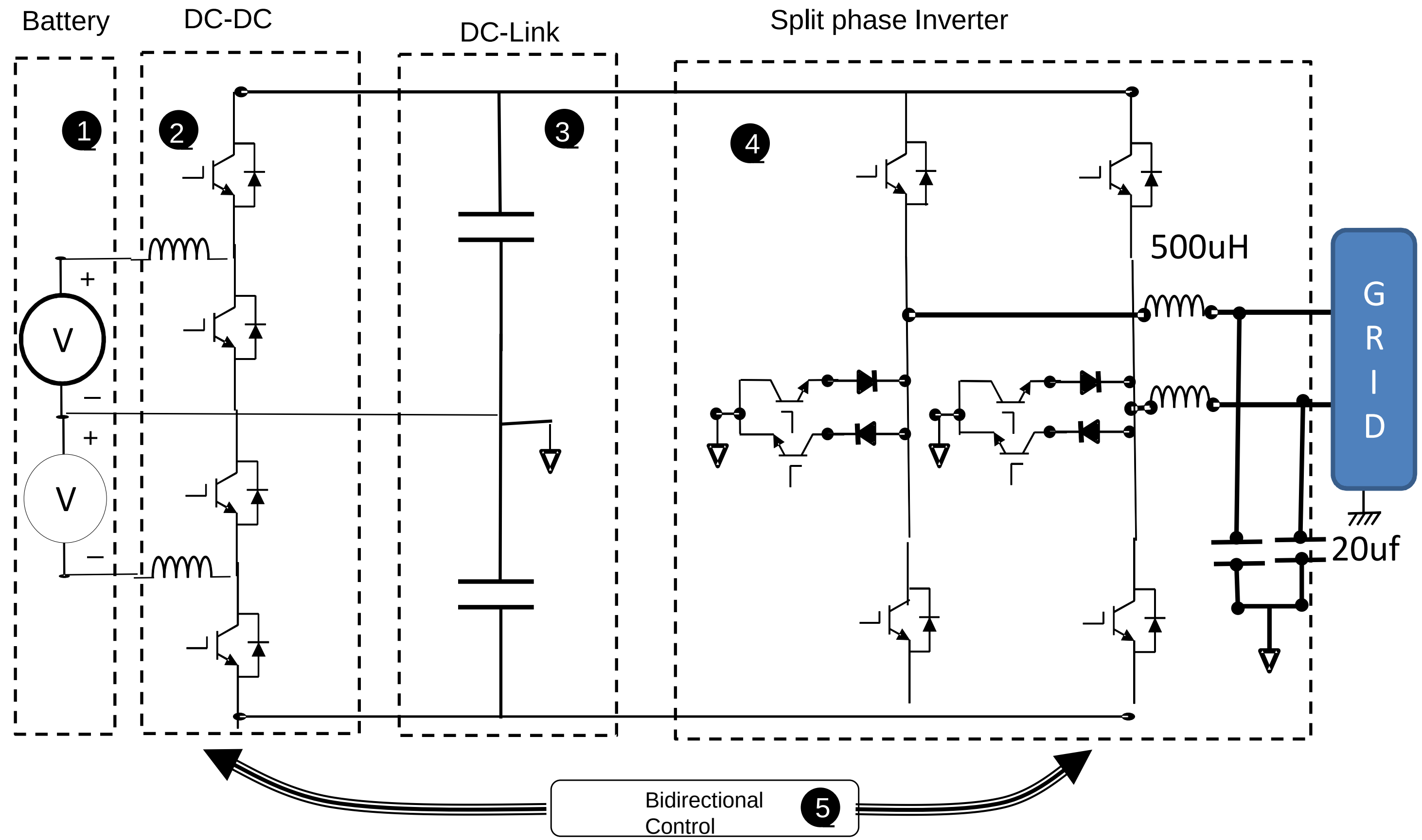
Transformerless Design _Motivation

- Cost reduction with additional weight and size reduction
- Efficiency increase and low cost

Average Parameter Comparisons for PV Inverters up to 6.5kW

	Transformerless	LF-Transformer	HF-Transformer
Avg. Efficiency (%)	95.7	94.5	94.1
Avg. Power per Weight (kW/kg)	0.213	0.0753	0.168
Avg. Power per Volume (kW/m^3)	115.2	84.7	80.2

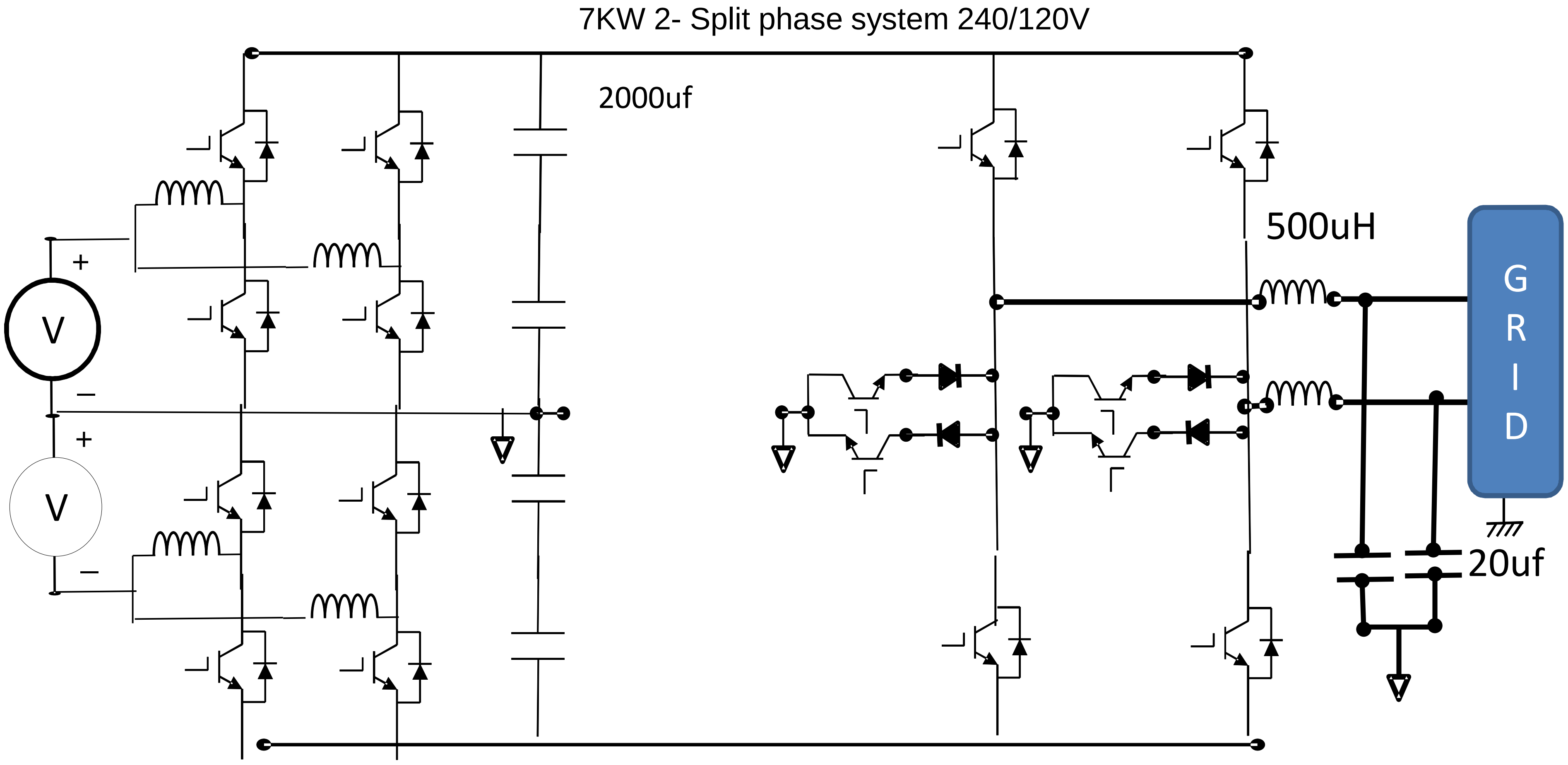
EXAMPLE OF TRANSFORMERLESS INVERTER



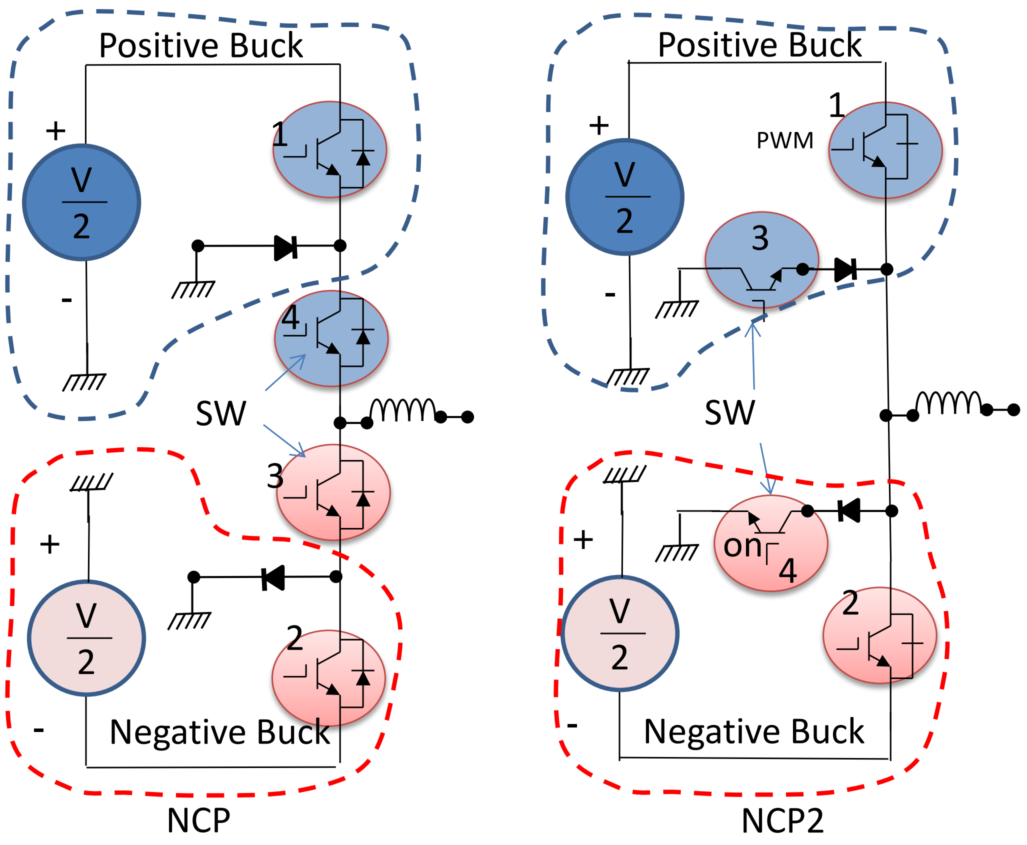
[INVERTER DEVICE, ENERGY STORAGE SYSTEM AND METHOD OF CONTROLLING AN INVERTER DEVICE]

Publication number: 20170077836

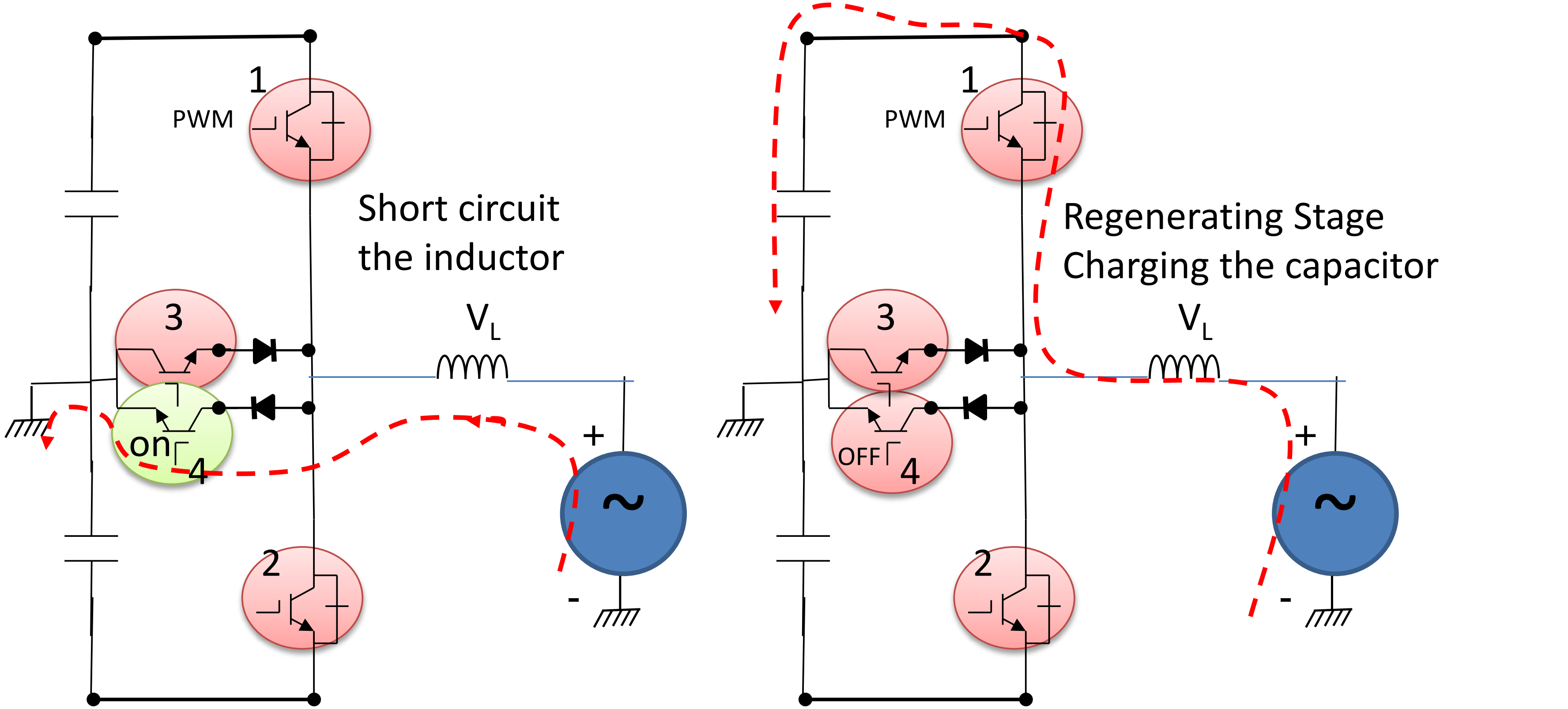
With interleaving



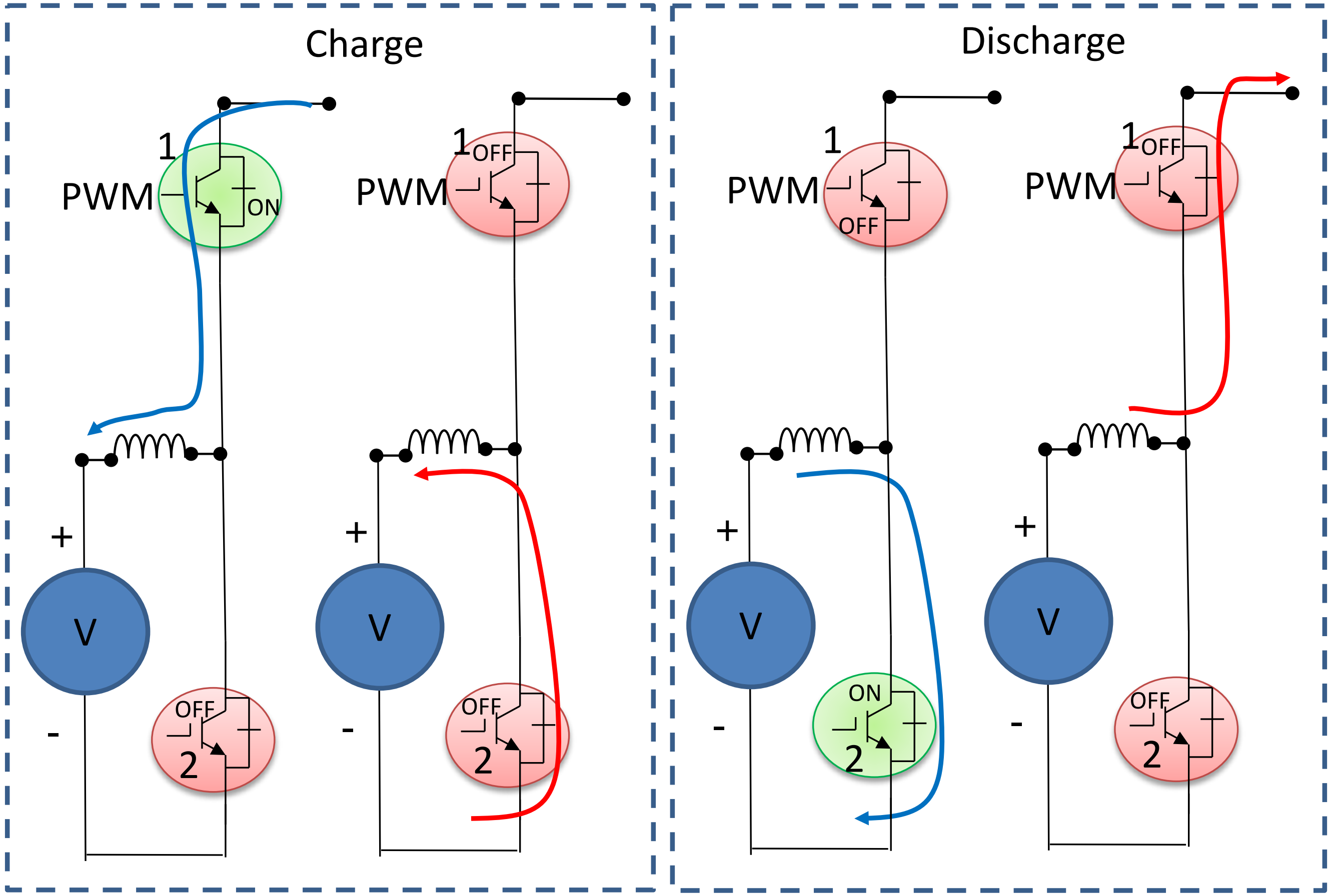
Principle of Operation 3-Level



Reverse energy transfer



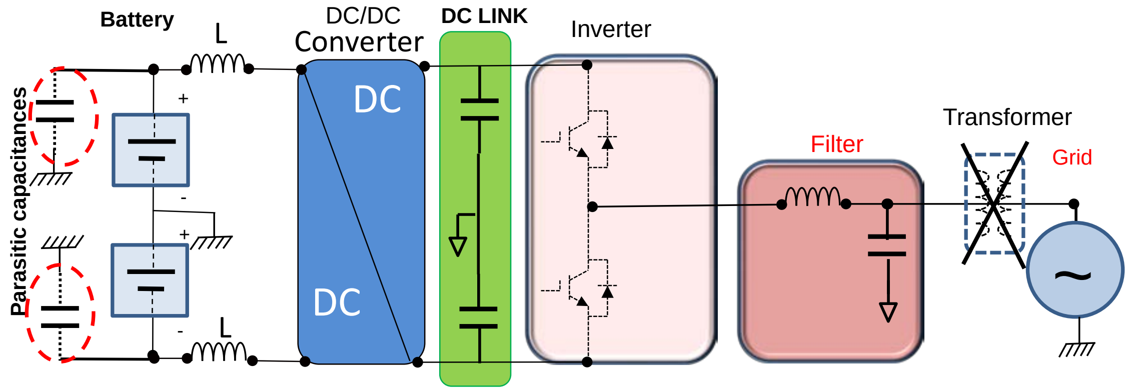
DC/DC basic operation



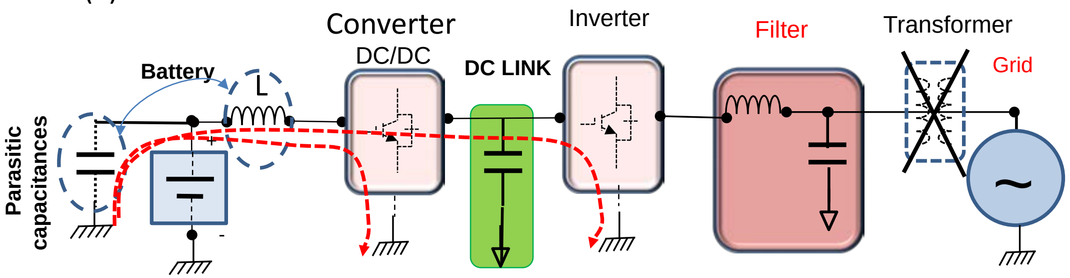
TRANSFORMERLESS OPERATION

$$V = \int_0^d E dz = \frac{Q.d}{\varepsilon_o A} \Rightarrow C = \frac{V}{Q} = \frac{\varepsilon_o A}{d}$$

A: total area of the plate
D: distance between the plates
εo: permittivity constant
8.8541× 10−12 F/m

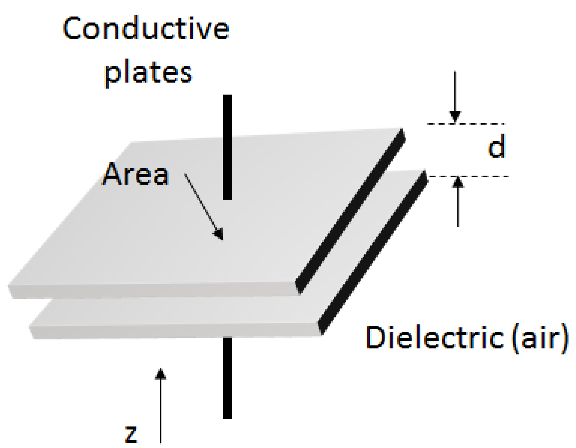


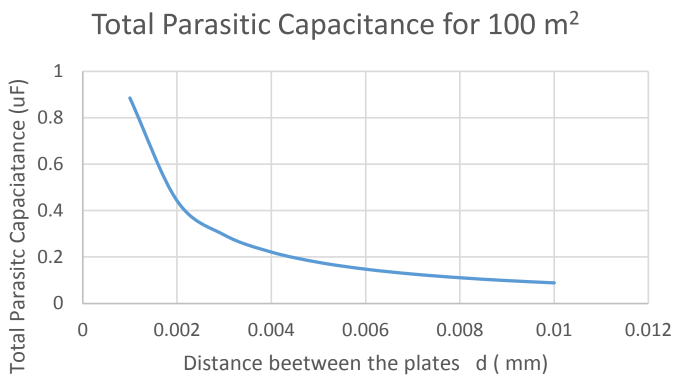
(a)

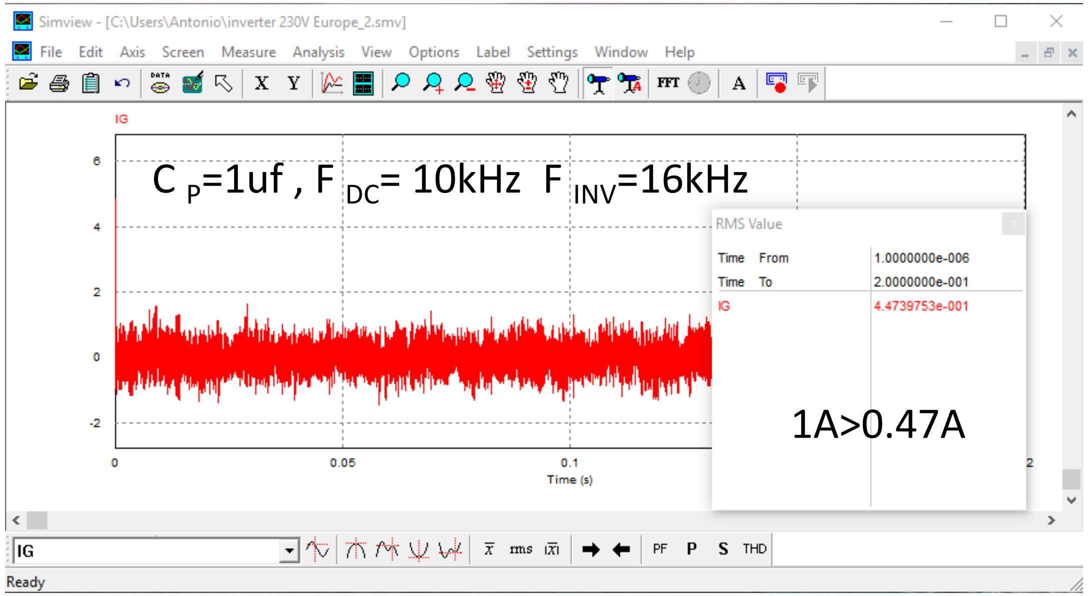


(b)

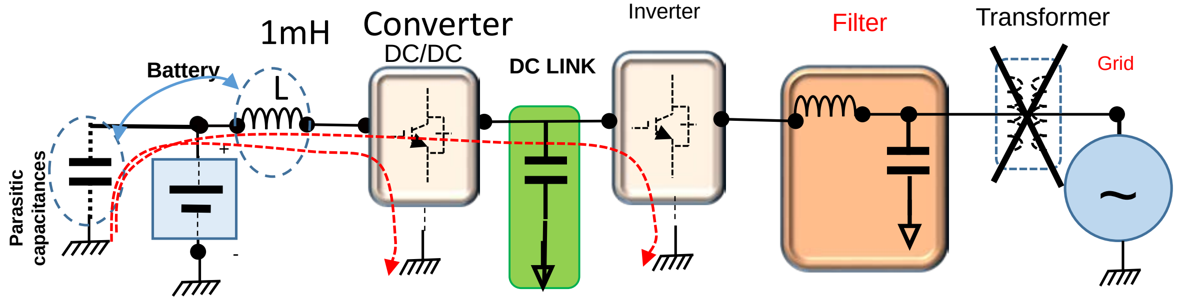
Ground current for 1uF total parasitic capacitance







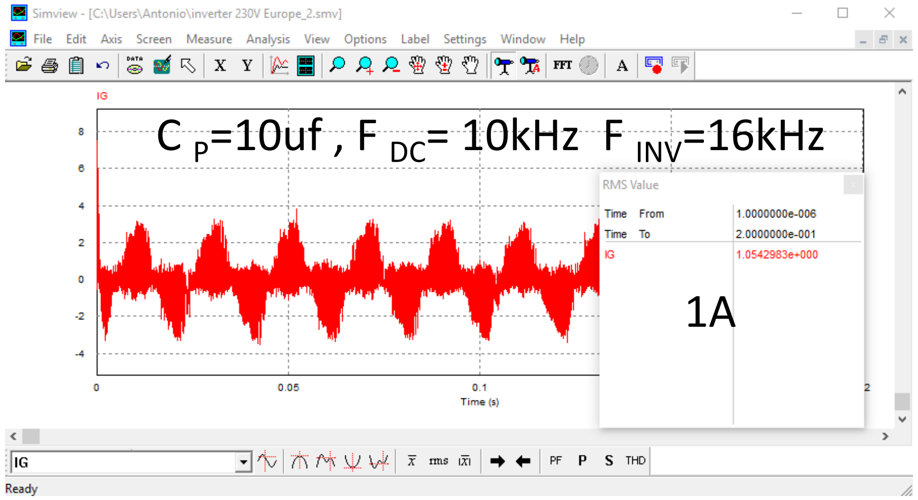
Evaluation Ground Current UL 1741

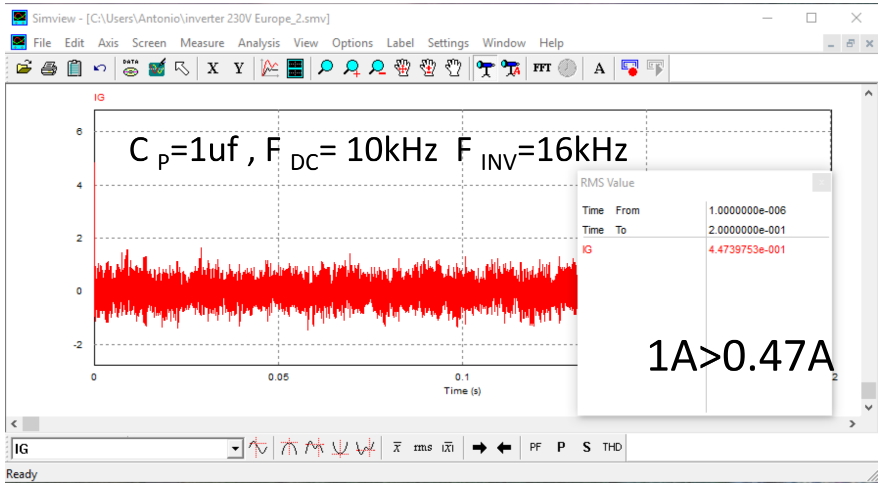


UL 1741 Ground Fault Detection Specifications vs. Inverter DC Rating

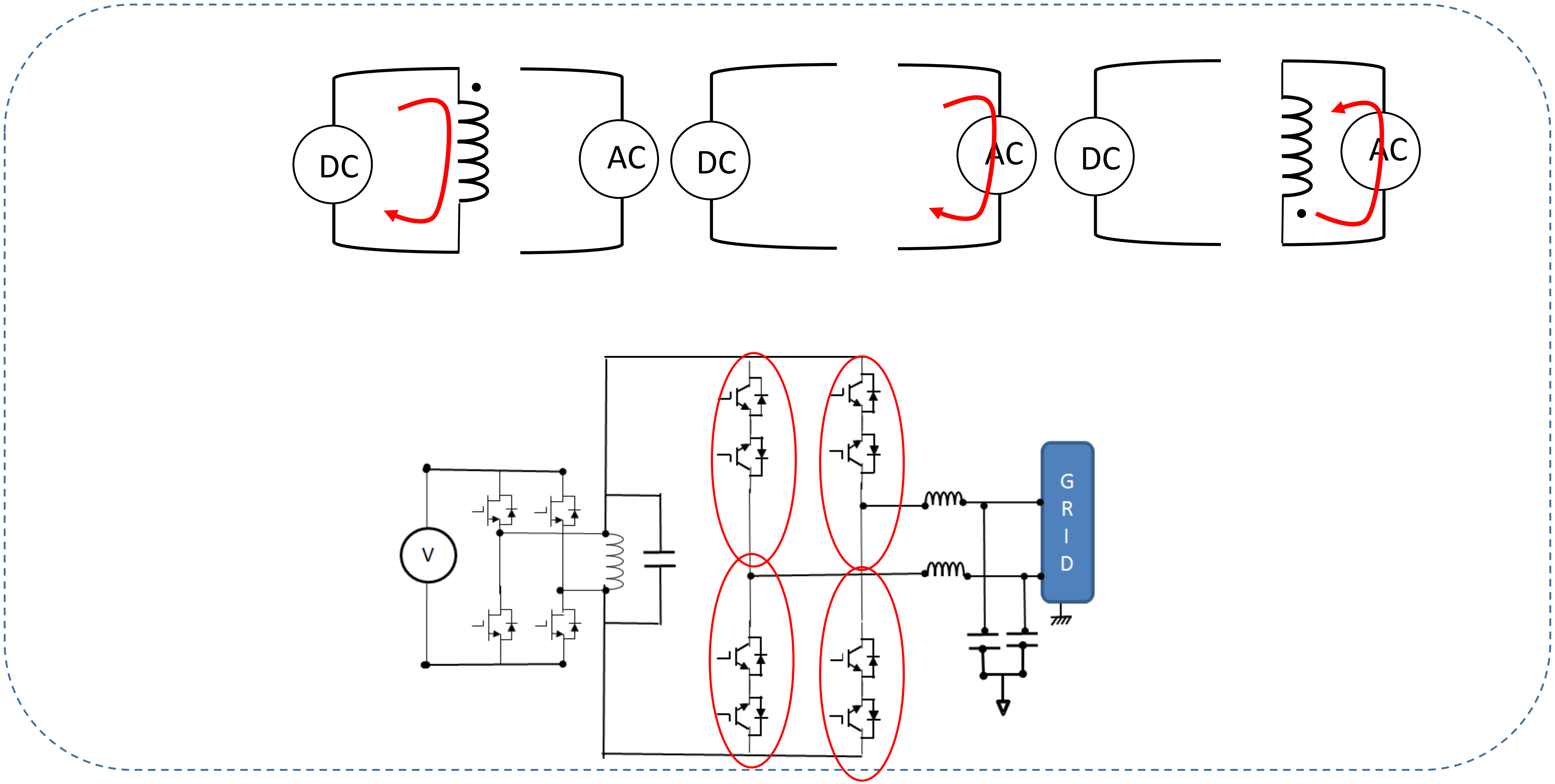
Inverter DC Rating (kW)	Maximum Ground Fault Current (Amps)
0-25	1
25-50	2
50-100	3
100-250	4
>250	5

Note: kW = kilowatts

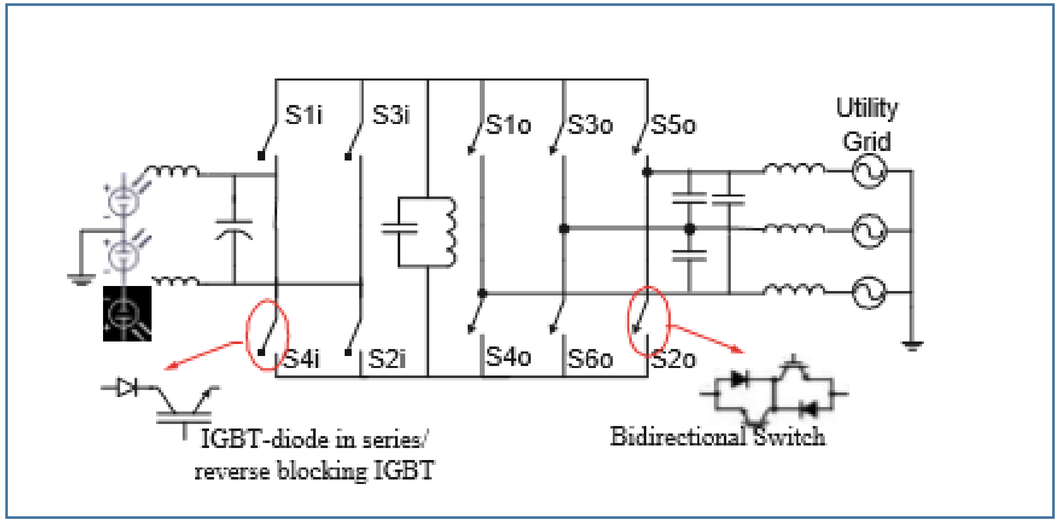


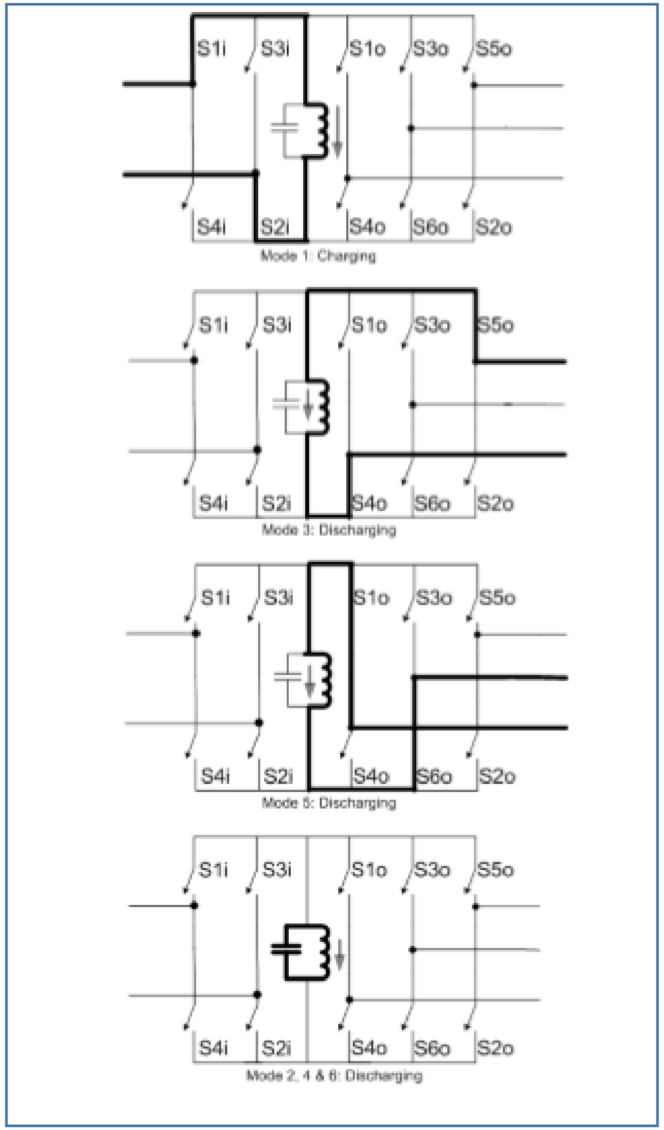


Current Based Bi-directional inverter



AC-link and bidirectional switches



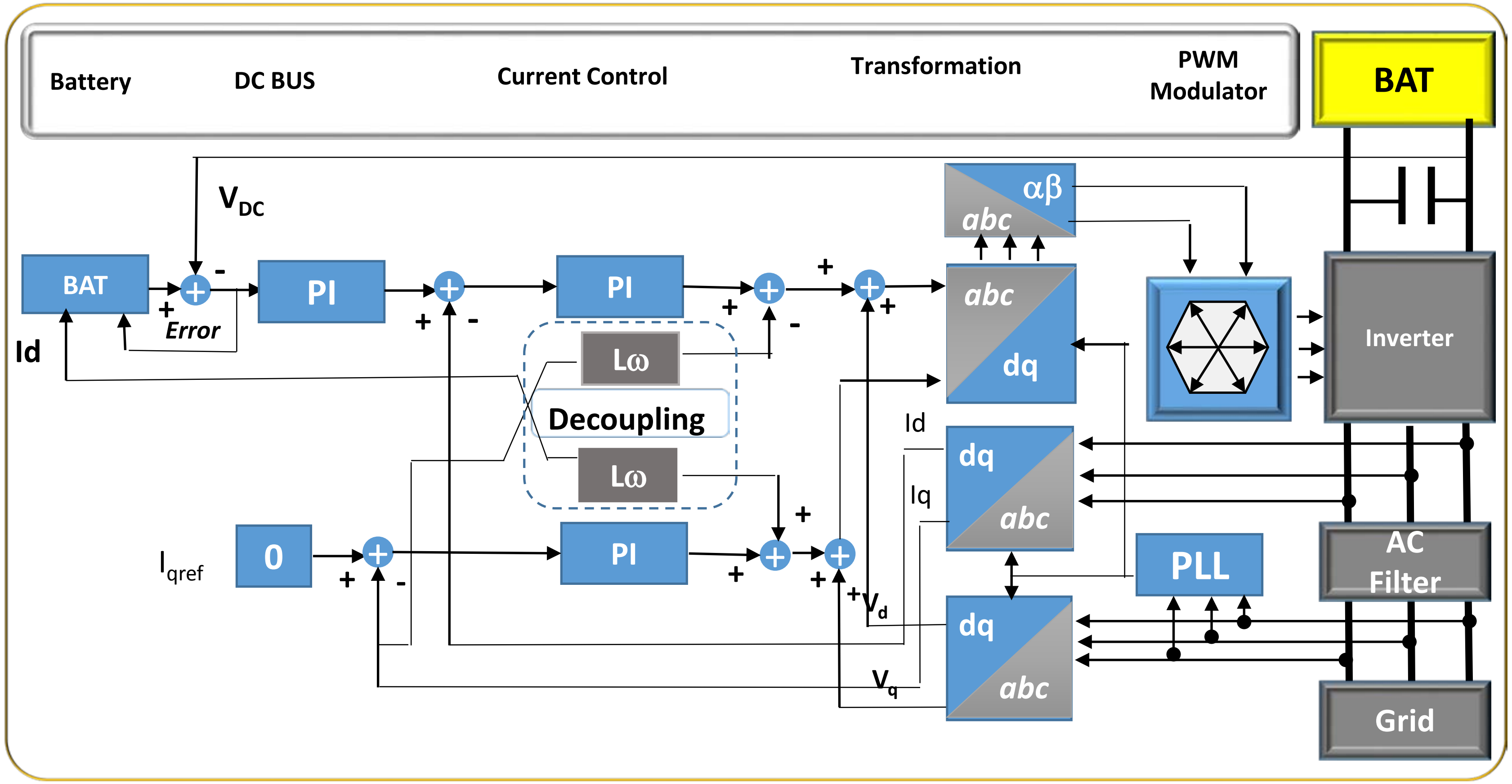


SOFT SWITCHED HIGH FREQUENCY AC-LINK CONVERTER

ANAND KUMAR BALAKRISHNAN

Inverter tied-grid control

Generalized d,q control



POWER RELATION BETWEEN A BATTERY SYSTEM AND A SINGLE PHASE AC SYSTEM

$$P_{DC} = I_{DC}.V_{DC} = \eta \cdot I_{RMS}.V_{RMS} = P_{AC}$$

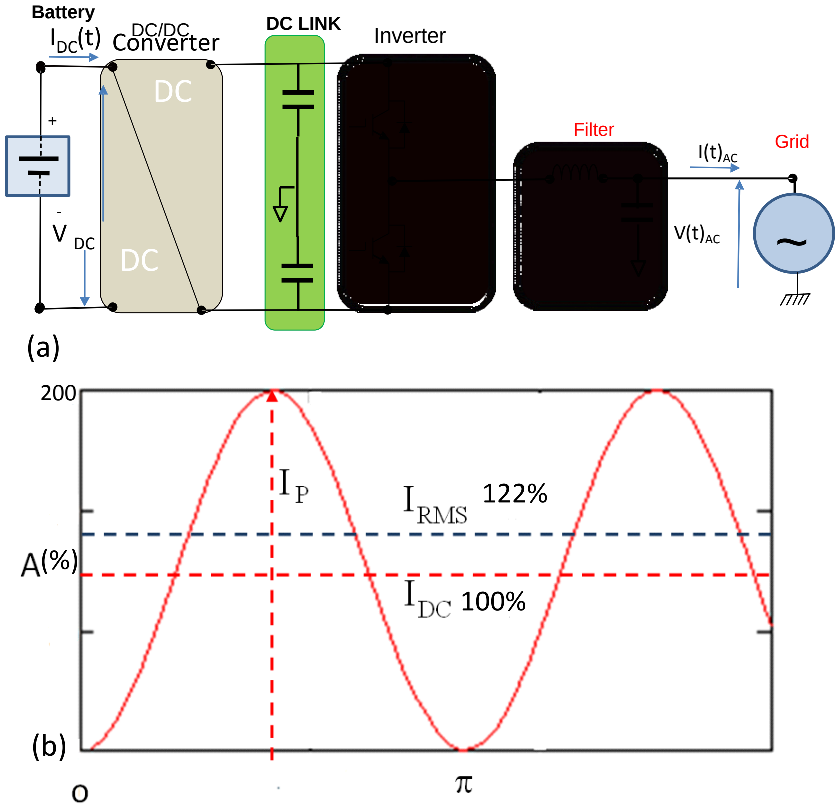
$$I_{DC}(t) = 2I_{DC}\sin^2(\omega t)$$

$$V_{DC}I_{DC} = V_{RMS}\sqrt{2}\sin(\omega t)I_{RMS}\sqrt{2}\sin(\omega t) \Rightarrow$$

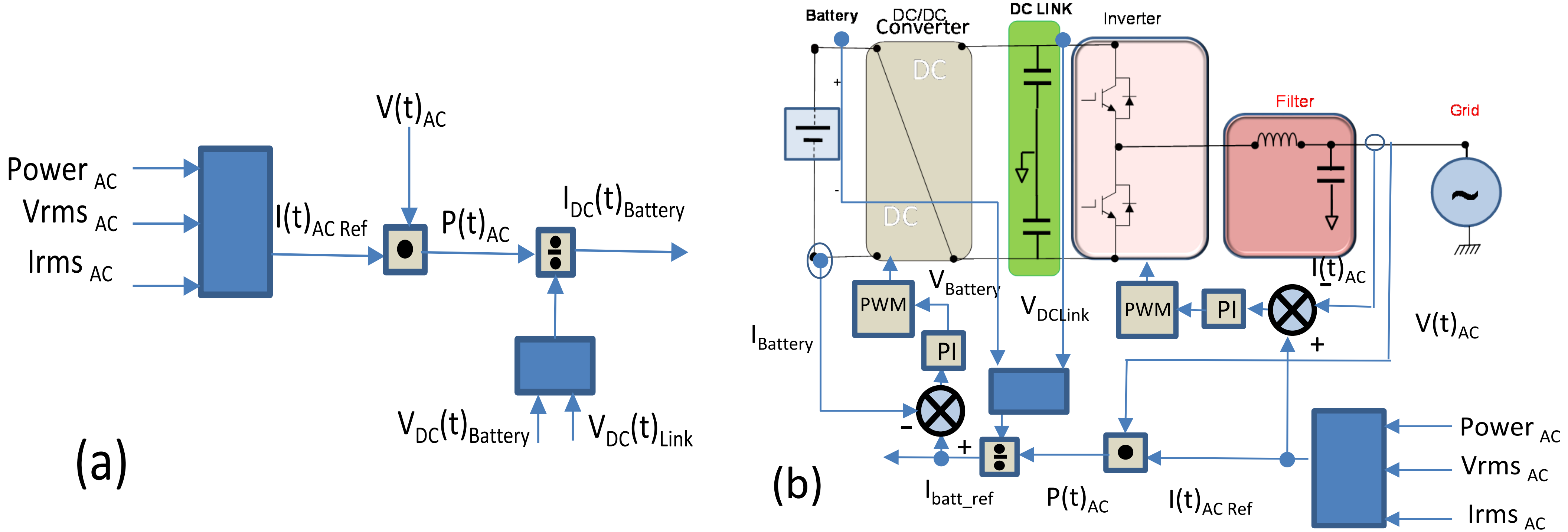
$$V_{DC}I_{DC} = 2V_{RMS}I_{RMS}\sin^2(\omega t)$$

$$I_{DC} = \frac{1}{\pi}\int_0^{\pi} I_P \sin^2(\alpha)d\alpha = \frac{1}{2}I_p$$

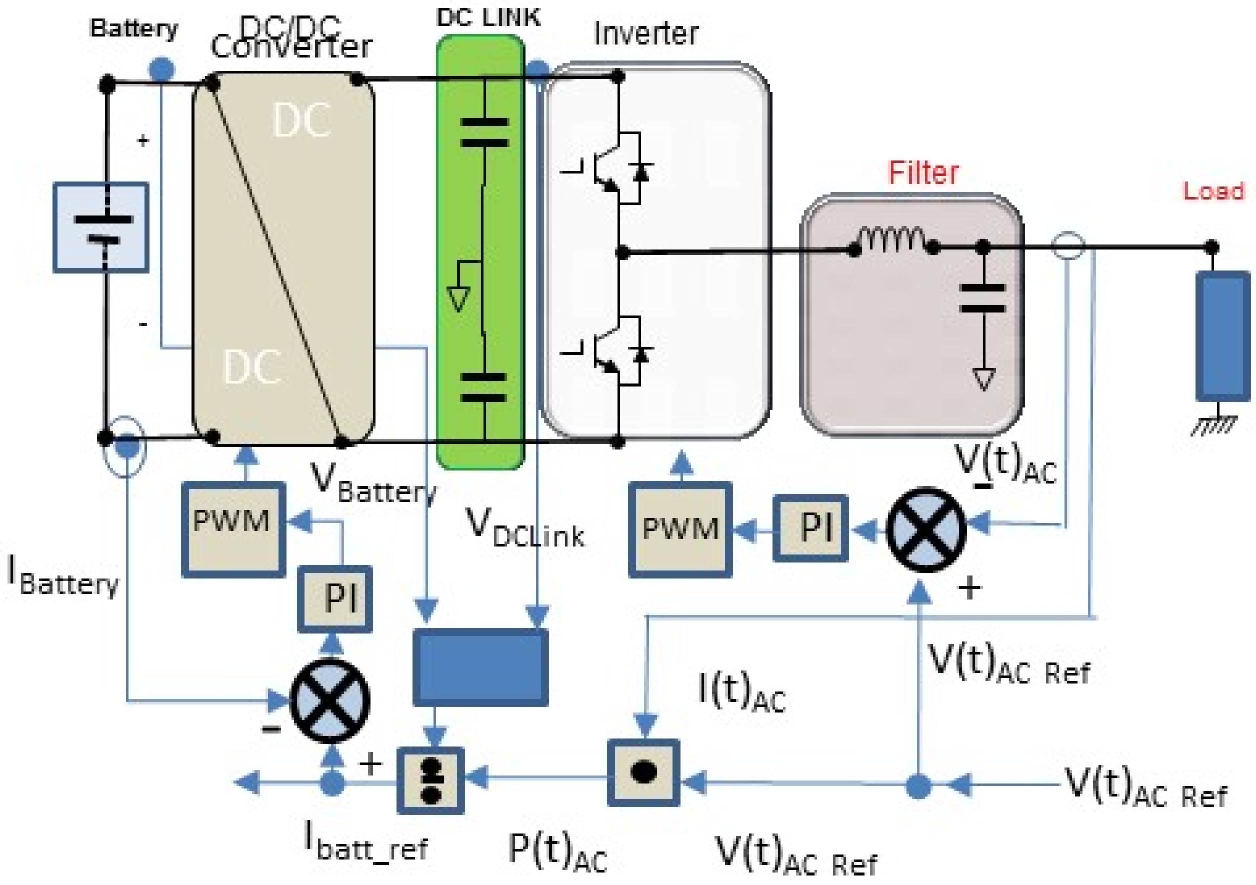
$$I_{RMs} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_P^2 \sin^4(\alpha)d\alpha} = \frac{\sqrt{3}}{2\sqrt{2}}I_p$$



Inverter Control

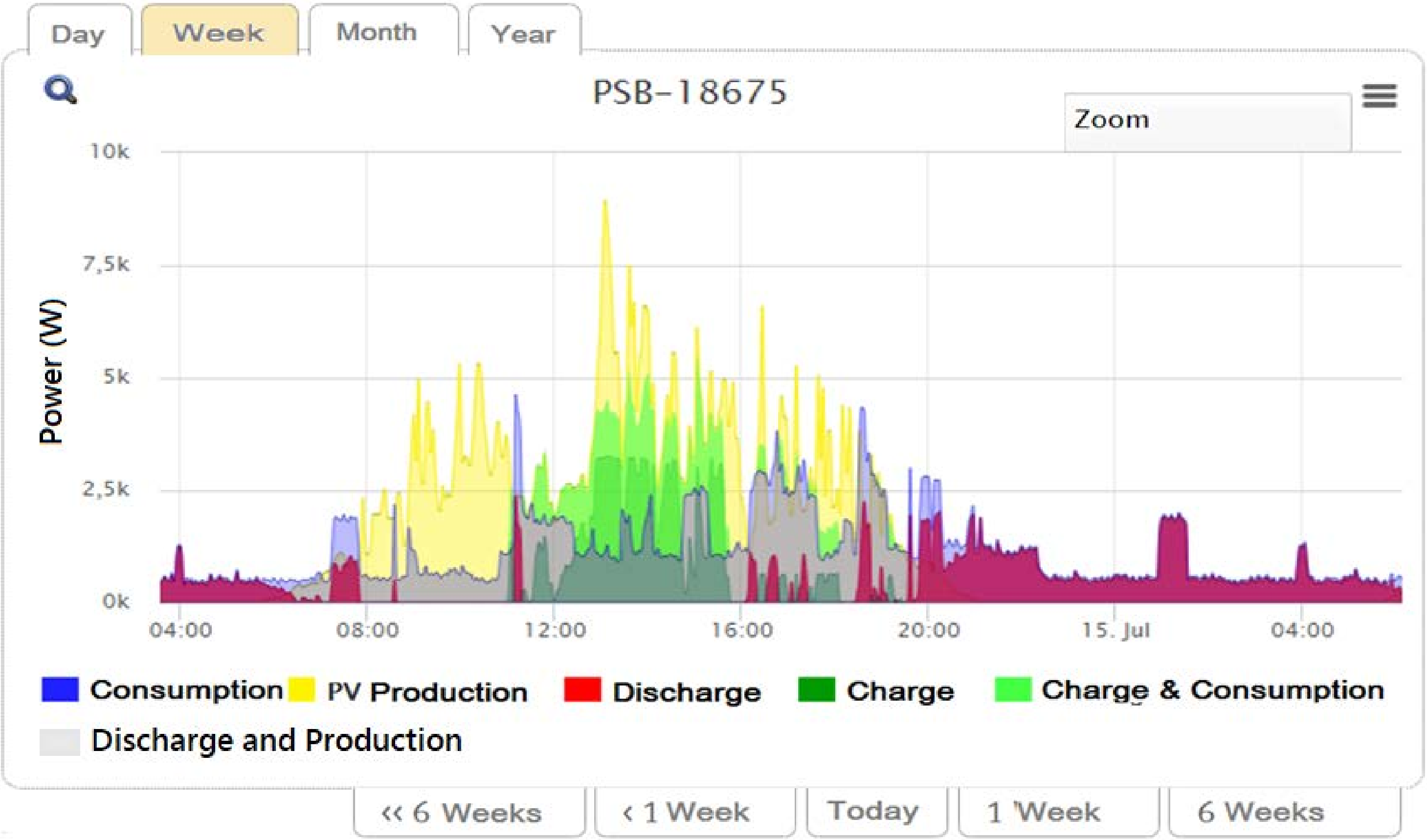


Stand Alone



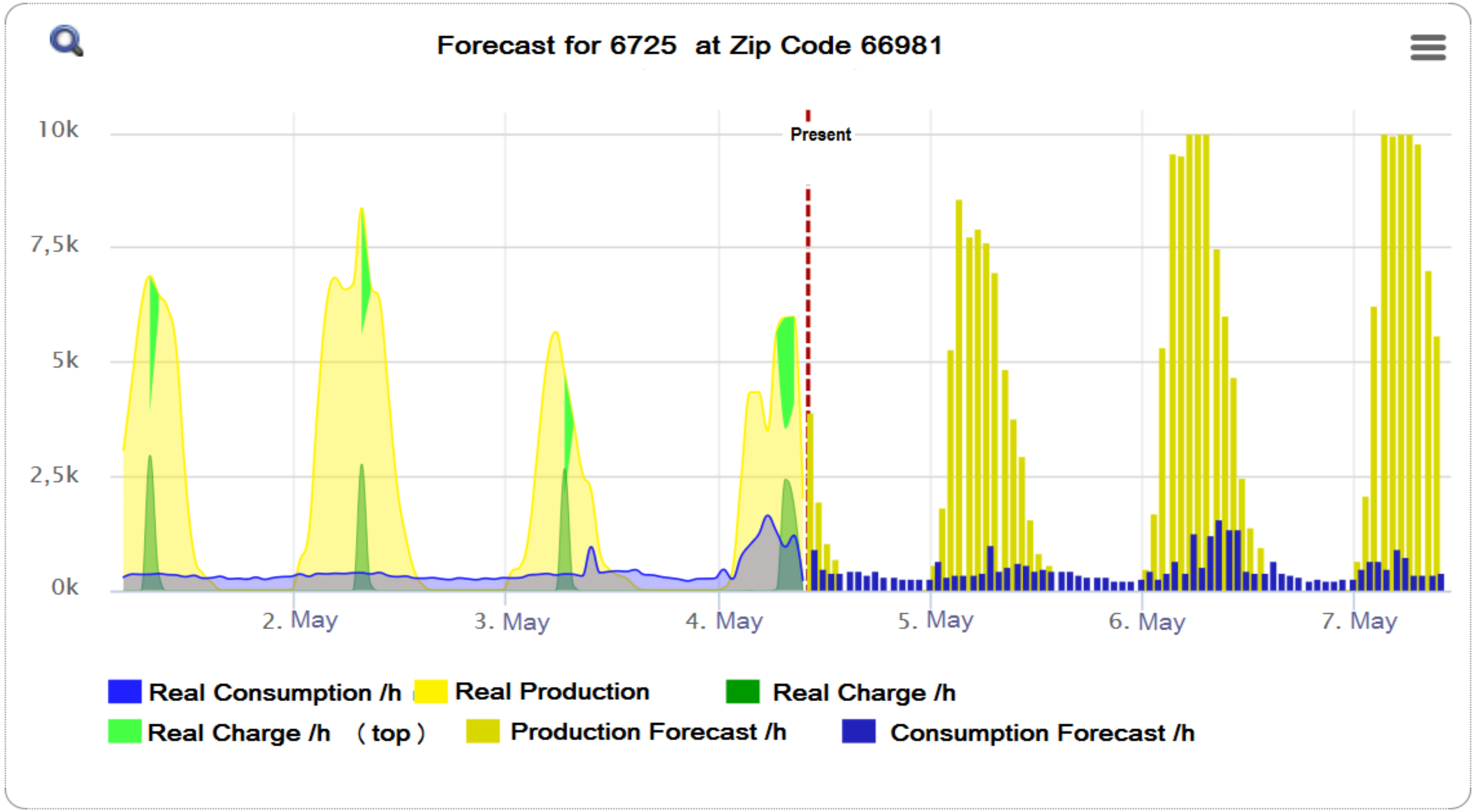
Battery
DC/DC Converter
DC LINK
Inverter
DC
DC
+
-
Filter
Load
V(t)AC
VBattery
VDCLink
PWM
PI
PWM
PI
IBattery
+
-
+
V(t)AC Ref
I(t)AC
V(t)AC Ref
Ibatt_ref
P(t)AC
V(t)AC Ref

GUI



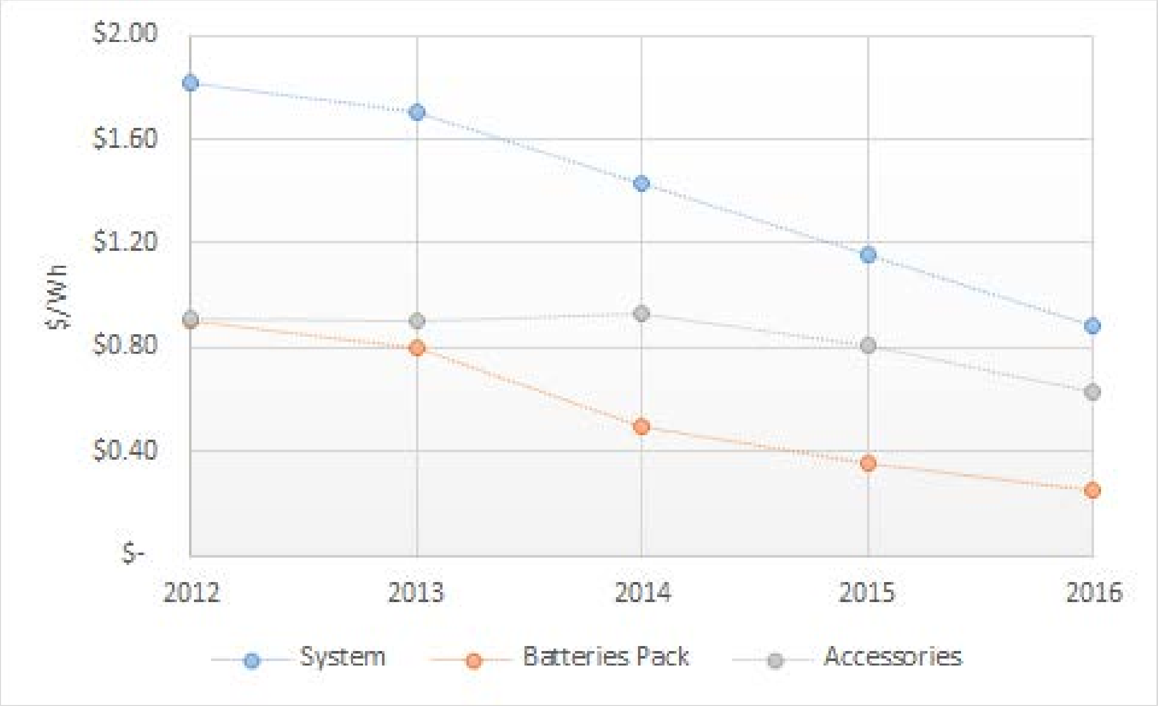
Day
Week
Month
Year
PSB-18675
Zoom
10k
7,5k
5k
2,5k
0k
Power (W)
04:00
08:00
12:00
16:00
20:00
15. Jul
04:00
Consumption
PV Production
Discharge
Charge
Charge & Consumption
Discharge and Production
« 6 Weeks
‹ 1 Week
Today
1 Week
6 Weeks

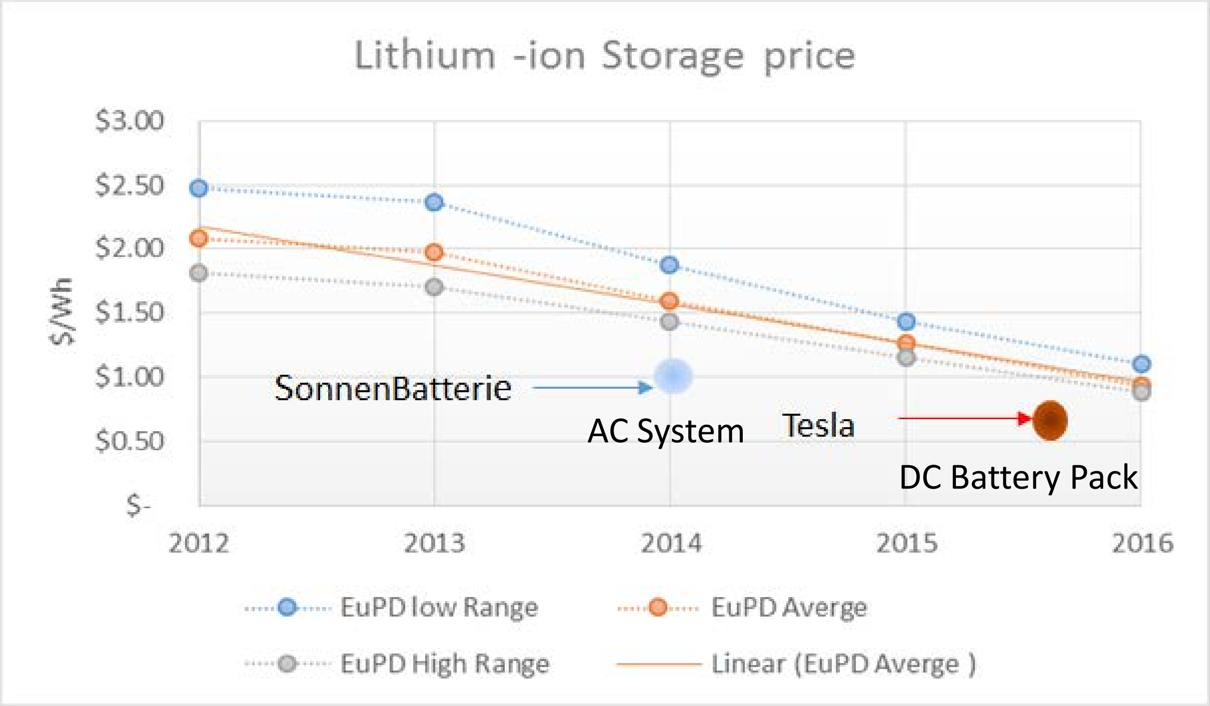
GUI and Weather Prediction



Energy Storage Prices

- 10,000 cycles and/or 10 years, 80% charge

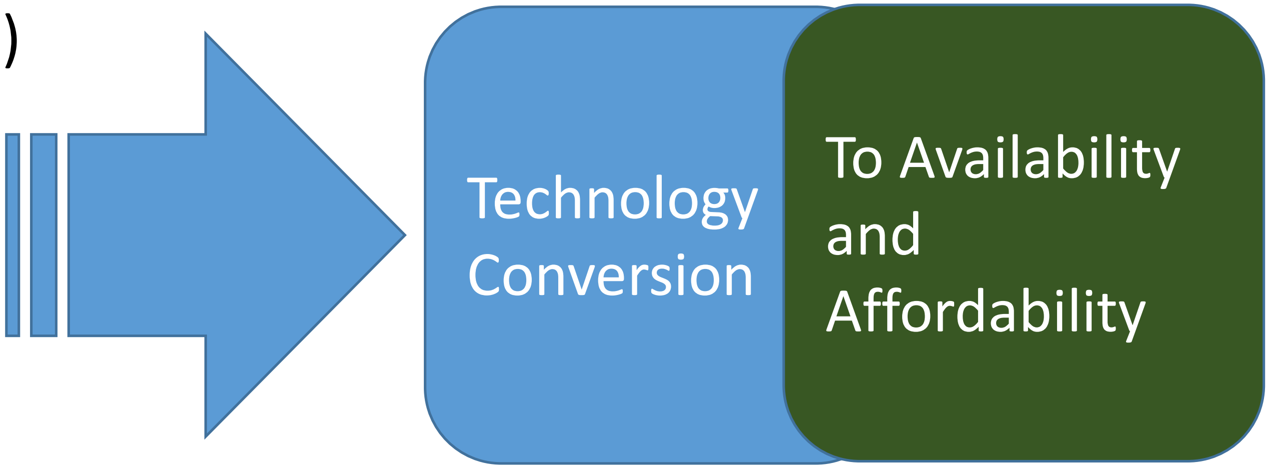




http://eupd-research.com/

Nanogrid-Energy Storage: Why Now?

- ❑Renewables Intermittence (generate “the need”)
- ❑Price (large price reduction)
- ❑Regulation (zero export to the grid)
- ❑Tariffs (peak demand)
- ❑Weather Prediction via Internet
- ❑Power grid reliability and safety
- ❑Smart Grid



Thanks!
Questions?