1st APSCO & ISSI-BJ Space Science School

Satellite System Engineering

-- Power System Design

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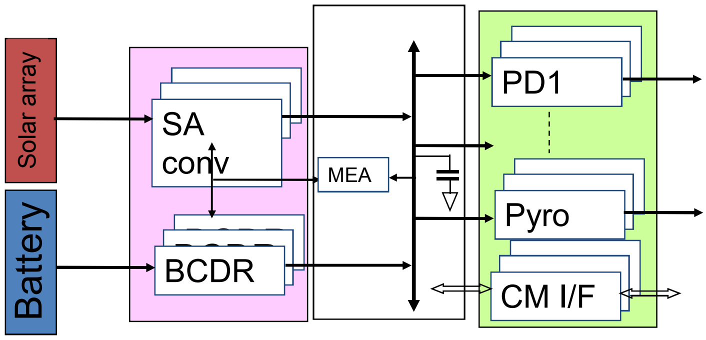
Introduction

- Power System Functions
- The Power System Design Process
  - Power System Requirements
  - Power System topology
  - Solar Array Configuration and Sizing Model
  - Battery Sizing Model
  - PCU / PDU Sizing Model

Power System Functions

Power Generation

- **Provide the power required by the spacecraft from launch until the mission completion**
- Usually a **solar array** for near sun satellite applications, sometimes a Radio-Isotope Thermoelectric generator (RTG) for spacecrafts that have to operate at great distances from the sun



Energy Storage

- Store energy during sunlight
- Ensure a continuous source of electrical power during eclipses
- Complement the power source as needed (e.g. peak power demands, manoeuvres)

Power Conditioning

- Provide autonomous control of the power generation and energy storage
- Condition the power bus to a defined voltage range
- Provide command and telemetry capability for health check and control

Power Distribution

- Distribute the power to all the spacecraft loads
- Provide load switching capabilities
- Protect the power lines to avoid failure propagation between loads and EPS

The Power System Design Process

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Power System Architecture:

Preliminary Iterative Design Process

Process	Information Required	Derived Requirements
Identify Requirements	System level requirements : Mission Type (LEO, GEO, planetary, sun & eclipse periods etc.) Spacecraft Attitude Control Mission Lifetime Payload Definition	Design Requirements Spacecraft electrical **power/energy profile**
Select Power Source	Mission Type Spacecraft Attitude & Configuration Average electrical power load requirements	EOL power requirements Type of solar cell Mass and area of solar array Solar array configuration
Select Energy Storage	Mission orbit parameters (e.g. eclipse) Average and peak electrical power load requirements	Energy needs for eclipses and peak power phases Battery type Battery mass and volume
Identify Power Conditioning Topology	Power source selection Mission lifetime Load type (e.g. pulsed, electrical propulsion, high.medium/low power…)	Peak-power tracker or direct energy transfer system Bus quality Power control algorithms

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Power Source Trades

– Earth Orbiting Spacecraft

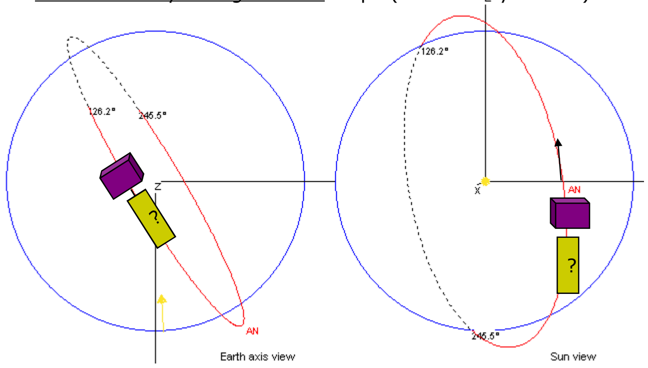
✓Power source is usually solar arrays and secondary batteries.

✓SA Configuration depends on range of angles between sun vector and orbit plane

✓Solar array will have minimum area when array surface is normal to sun vector

✓Solar array size increases with mission design life

✓Key design trade is the Solar Array Configuration: Shape (Planar or cylindrical) and Articulation (Fixed or Rotating)



Which solar array configuration/design would be the most attractive? ….

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Solar Array Configuration Trade – Earth Orbiting Spacecraft Array Configurations

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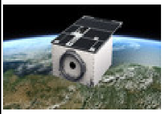
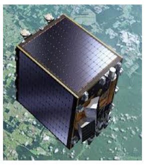
Configuration 1 | Configuration 2 | Configuration 3

Body Mounted solar array

TerraSAR-X
DMC-G2
EnMAP



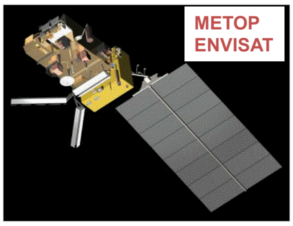
Proba-V



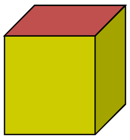
Deployed wings with SADM

ADM-Aeolus
MEX
VEX

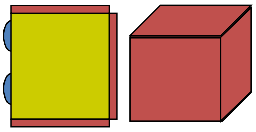
Canted deployed wings with SADM

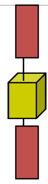


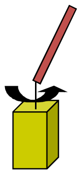
Configuration 1.a



Configuration 1.b







Sun Inclination: ± 5°

↓

Illumination Factor > 0.996

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Trade Solar Array Configuration

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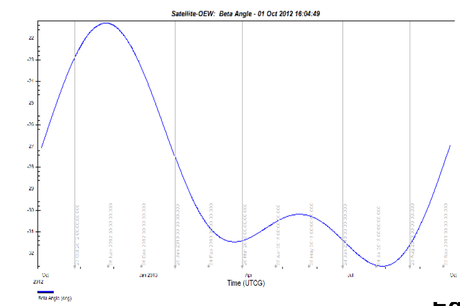
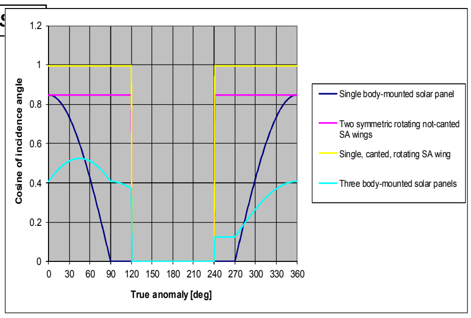
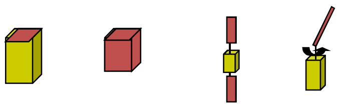
Beta angle evolution: Angle between normal to orbit and S





Equivalent worst solar incidence angle [deg]



62	**68**	**32**	**5**

Which configuration to select?

Which impact on the other subsystems?

Power Budget

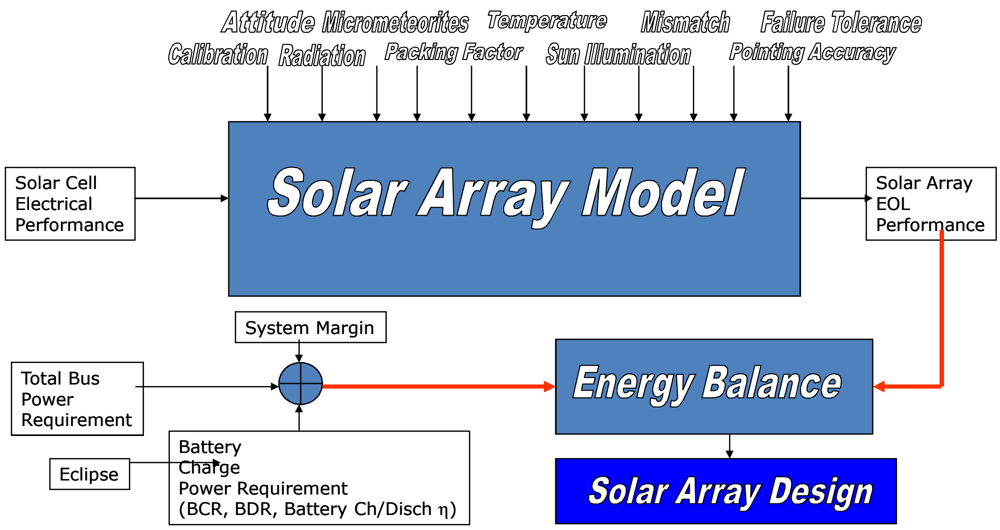
Modes	Sizing for		Subsystems	Thermal	AOCS	Comms	Propulsion	DHS	Mech	OC sensor	SST Sensor	Altimeter	Harness (excl. PSS)	TOTAL CONSUMPTION
				linked	linked	linked	linked	linked	linked	linked	linked	linked		
			Ppeak	0 W	135 W	0 W	30 W	58 W	6 W	46 W	138 W	142 W	11 W	566 W
Launch Mode	Battery	Solar Flux 0 W/m² (0 if Solar Array not used)	Pon	40 W	10 W	34 W	0 W	58 W	0 W	0 W	0 W	0 W	3 W	144 W
			Pstdby	40 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	1 W	41 W
			Duty Cycle	0 %	100 %	100 %	0 %	100 %	0 %	0 %	0 %	0 %		100%
Tref 73 min		Eclipse Mode NOT Included	Total Wh	49 Wh	12 Wh	41 Wh	0 Wh	70 Wh	0 Wh	0 Wh	0 Wh	0 Wh	3 Wh	175 Wh
Initialisation Mode	Battery	Solar Flux 0 W/m² (0 if Solar Array not used)	Pon	120 W	137 W	34 W	10 W	58 W	5 W	0 W	0 W	12 W	8 W	383 W
			Pstdby	120 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	2 W	122 W
			Duty Cycle	0 %	100 %	100 %	100 %	100 %	100 %	0 %	0 %	100 %		100%
Tref 120 min		Eclipse Mode NOT Included	Total Wh	240 Wh	273 Wh	68 Wh	20 Wh	116 Wh	10 Wh	0 Wh	0 Wh	24 Wh	15 Wh	766 Wh
Operational Mode	Battery Solar Array	Solar Flux 1326 W/m² (0 if Solar Array not used)	Pon	60 W	149 W	111 W	10 W	58 W	5 W	46 W	138 W	142 W	14 W	733 W
			Pstdby	60 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	1 W	61 W
			Duty Cycle	0 %	100 %	36 %	100 %	100 %	100 %	100 %	100 %	100 %		89%
Tref 101 min		Eclipse Mode Included	Total Wh	101 Wh	250 Wh	67 Wh	17 Wh	98 Wh	8 Wh	77 Wh	232 Wh	239 Wh	22 Wh	1111 Wh
Eclipse Mode Eclipse Mode	Battery	Solar Flux 0 W/m² (0 if Solar Array not used)	Pon	140 W	149 W	111 W	10 W	58 W	5 W	0 W	138 W	142 W	15 W	767 W
			Pstdby	140 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	3 W	143 W
			Duty Cycle	0 %	100 %	36 %	100 %	100 %	100 %	0 %	100 %	100 %		88%
Tref 33 min		Eclipse Mode NOT Included	Total Wh	77 Wh	82 Wh	22 Wh	6 Wh	32 Wh	3 Wh	0 Wh	76 Wh	78 Wh	7 Wh	382 Wh
Safe Mode w/o sun pointing	Battery	Solar Flux 0 W/m² (0 if Solar Array not used)	Pon	140 W	19 W	51 W	10 W	58 W	5 W	0 W	0 W	12 W	6 W	300 W
			Pstdby	140 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	3 W	143 W
			Duty Cycle	0 %	100 %	100 %	100 %	100 %	100 %	0 %	0 %	100 %		100%
Tref 60 min		Eclipse Mode NOT Included	Total Wh	140 Wh	19 Wh	51 Wh	10 Wh	58 Wh	5 Wh	0 Wh	0 Wh	12 Wh	6 Wh	300 Wh
Orbit Maintenance Mode	Solar Array	Solar Flux 1326 W/m² (0 if Solar Array not used)	Pon	70 W	149 W	51 W	10 W	58 W	5 W	0 W	0 W	12 W	7 W	362 W
			Pstdby	70 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	1 W	71 W
			Duty Cycle	0 %	100 %	69 %	100 %	100 %	100 %	0 %	0 %	0 %		90%
Tref 101 min		Eclipse Mode NOT Included	Total Wh	118 Wh	250 Wh	59 Wh	17 Wh	98 Wh	8 Wh	0 Wh	0 Wh	0 Wh	11 Wh	561 Wh
De-Orbiting Mode	Solar Array	Solar Flux 1326 W/m² (0 if Solar Array not used)	Pon	160 W	137 W	51 W	10 W	58 W	5 W	0 W	0 W	0 W	8 W	429 W
			Pstdby	160 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	3 W	163 W
			Duty Cycle	0 %	100 %	100 %	100 %	100 %	100 %	0 %	0 %	0 %		100%
Tref 101 min		Eclipse Mode NOT Included	Total Wh	269 Wh	230 Wh	86 Wh	17 Wh	98 Wh	8 Wh	0 Wh	0 Wh	0 Wh	14 Wh	722 Wh
Safe Mode Coarse Pointing	Solar Array	Solar Flux 773 W/m² (0 if Solar Array not used)	Pon	140 W	19 W	51 W	10 W	58 W	5 W	0 W	0 W	12 W	6 W	300 W
			Pstdby	140 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	3 W	143 W
			Duty Cycle	0 %	100 %	100 %	100 %	100 %	100 %	0 %	0 %	100 %		100%
Tref 101 min		Eclipse Mode NOT Included	Total Wh	236 Wh	31 Wh	86 Wh	17 Wh	98 Wh	8 Wh	0 Wh	0 Wh	20 Wh	10 Wh	506 Wh

Pre –Phase A

20% PDR

5% Launch

Solar Array Model Overview



Solar Array Sizing

1. Determine orbit period (T), maximum eclipse time (Te) and minimum sunlight time (Ts) for an orbit altitude of 780 km.
   T = 100.6 min   Te = 34.4 min   Ts = 66.1 min

2. Determine required power during eclipse (Pe) and sunlight (Ps)
   Ps = Pe = 790 W

3. Compute Psa (Produced solar array power)
   Psa *ξ_{SAC} = Ps + Pcharge (Battery charging power)
   Pcharge *ξ_{charge}*$\xi_{discharge}$ = Pe*Te/Ts

Ideal case when all ξ=1 → Psa = (PsTs+PeTe)/Ts → Psa = Ps*T/Ts

ξ = path efficiencies

(Topologies with **Regulated Bus**)	MPPT	Direct Energy Transfer (DET)
ξ_{SAC}	0.9	0.95

Bus topology	Regulated	Unregulated
ξ_{charge}	0.9	0.95
$\xi_{discharge}$	0.9	0.95

- **Please consider these figures only as indicative**

Solar Array Sizing

4. Determine Po Ideal output of the solar cells assuming that the sun vector is perpendicular to their surface, based on solar cell type.

η@ AM0(27° C) x packing factor (90/95%)
η x temperature effect
η(in typical LEO/GEO environment)

Si   Po = 0.148 x (1367 W/m2) = 202 W/m2
GaAs(TJ)   Po = 0.220 x (1367 W/m2) = 301 W/m2

5. Determine BOL power production capability (Pbol)

   Obtain initial loss factors (Id)= 0,936

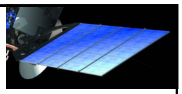
6. Determine worst case solar incidence angle S
   (angle between solar array normal and Sun Vector)

   S = 5 degrees

7. Compute Pbol = Po x Id x cosS =

T-indip effect	Degradation factor
Coverglass	0.995
Mismatch + Calibration	0.970
UV + Micrometeorites	0.990
Random failure	0.980
Pointing error	0.99985
Total	**0.936**

Solar Array Sizing



8. Determine EOL power production capability (Peol).
   Assume fractional degradation per year, say 3.75%.
   Calculate degradation for 7 years life.
   Ld = (1 - degradation)/year)^satellite life
   Ld = $(1-0.0375)^7$ = 0.77

9. Compute:
   Peol = Pbol x Ld =   *(≅200 W/m2 for TJ)*

10. Estimate array size
   A = Psa/Peol =

11. Estimate mass of the solar array
   M = m x A =

   m = 4.5 kg/m2 for deployable SA
   2.7kg/m2 for body mounted PVA

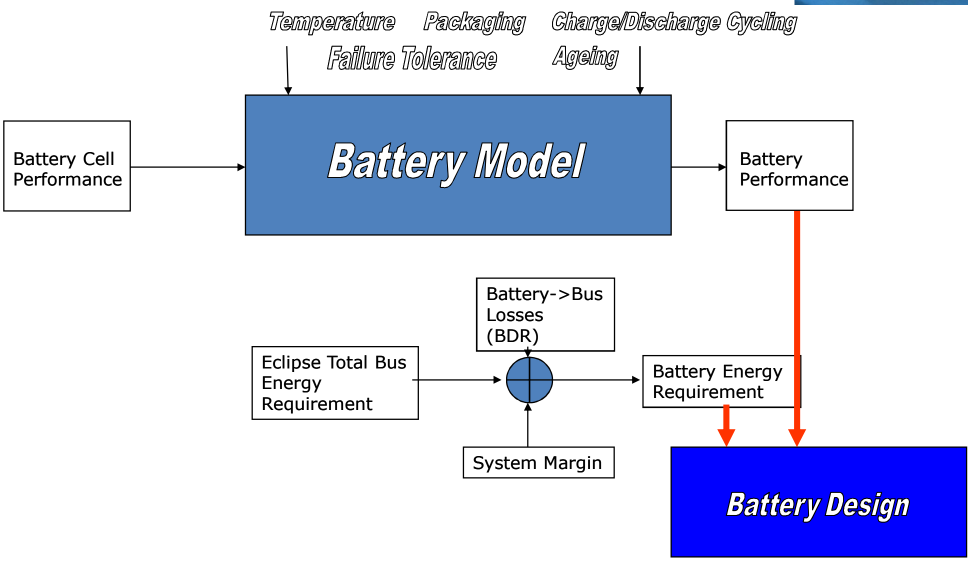
Power Profile (with System Margin):
Average Sunlight (67min):
* Pon = 879W
* Pstdby = 73W
* Duty Cycle = 89%

Average Eclipse (34min):
* Pon = 921W
* Pstdby = 171W
• Duty Cycle = 88%

Energy Need: 459 Wh

Battery design

Battery Model



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Battery technologies

Figures Of Merits

NiH2 Rechargeable:
• Battery Level: 50Wh/kg 70Wh/l

Li-Ion Rechargeable
(based on 18650HC (*)):
• Cell Level: 133Wh/kg 320Wh/l
• Battery Level: 100Wh/kg 130 Wh/l

Selection of Battery Cells
=> BOL: Wh/kg , Wh/l

Li-Ion Rechargeable (in qualification)
(based on 18650LV (*))
• Cell Level: 175Wh/kg 450Wh/l
• Battery Level: 130Wh/kg 170Wh/l

(*) Similar performance for other European battery suppliers

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Battery Sizing

1. Degradation of the cells:
   – Li-ion: Typically:
     LEO Mission: 30% capacity remaining at EOL -> 30% Max Dod to be considered
     GEO Mission: 70% capacity remaining at EOL-> 70% Max Dod to be considered

2. Tolerance to Single Failure (Loss of one cell in Open or Short)
   – Typically one additional string (small battery cells assembly)
   => first guess: +5% extra cells

3. Packaging cells: +25% mass

1. Battery Energy Required E_B
   E_B= Bus Energy Required *(1+0.05)/ (DoD*$\xi_{discharge}$)

=> Battery mass= E_B * Battery Wh/kg * (1+0.25) (+5% maturity margin)

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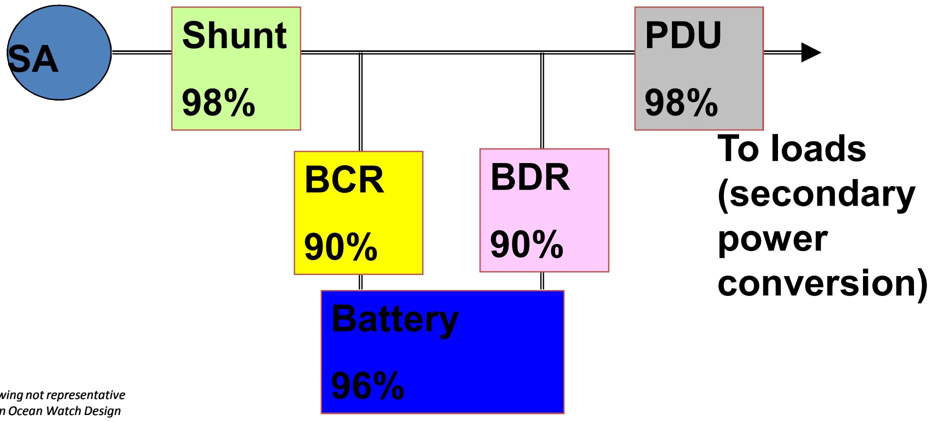
PCDU Model – example of regulated bus



Drawing not representative from Ocean Watch Design

- **Please consider these figures only as indicative**

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Power Budget

S/S Power Consumption	Launch Mode	Initialisation Mode	Operational Mode		Eclipse Mode	Safe Mode w/o sun pointing	Orbit Maintenance Mode	De-Orbiting Mode	Safe Mode Coarse Pointing
SubMode			Sunlight	Eclipse					
Duration (min)	72.77	120.00	68.00	33	33.00	60.00	101.00	101.00	101.00
Energy Budget (Wh)									
Total	175 Wh	766 Wh	729 Wh	382 Wh	382 Wh	300 Wh	561 Wh	722 Wh	506 Wh
Margin	20%	20%	20%	20%	20%	20%	20%	20%	20%
Total	210 Wh	919 Wh	875 Wh	459 Wh	459 Wh	360 Wh	673 Wh	866 Wh	607 Wh
Solar Arrays									
Power Generated	0 W	0 W	1403 W		0 W	0 W	1403 W	1403 W	796 W
Energy on the Bus	0 Wh	0 Wh	1526 Wh		0 Wh	0 Wh	2267 Wh	2267 Wh	1286 Wh
Battery Module									
Dod at the End of mode	12.9%	56.3%	0.0%		28.1%	22.1%	0.0%	0.0%	0.0%
Max allowable Dod (due to degradation)	80.0%	80.0%	0.0%		30.0%	30.0%	0.0%	0.0%	0.0%
Energy Budget									
Energy Margin on the Bus (Wh)	-276 Wh	-1207 Wh	29 Wh		-602 Wh	-473 Wh	1593 Wh	1400 Wh	679 Wh
Energy Margin on the Bus (%)	-131%	-131%	3%		-131%	-131%	237%	162%	112%

Battery & Solar Array can fulfill the power/energy requirements in all the modes

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Limitations of the design approach

- **The presented sizing process is meant to give a rudimentary first estimate of the different power system elements.**
- **It is based on general figures of merit that are application dependant (e.g. solar cells degradations due to radiation) and ignores some factors potentially relevant for some missions (SA blocking diodes, EMC & Regulation quality, need of balancing electronics for battery, solar flux seasonal fluctuations, albedo & thermal flux contributions….)**
- **The design should therefore be consolidated by using:**
  - Dedicated power system modeling tools
  - Dedicated power electronics modeling tools
  - Adequate power system and power conditioning expertise