HVDC Power Converter Project Review

Polarconsult Alaska Inc.

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Darren Hammell, Executive Vice President & Co-Founder
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Who is Princeton Power?

Princeton Power Systems designs and builds high-performance power electronic converters for military and commercial distributed generation applications, and designs and installs complete photovoltaic systems.

Our Distributed Generation Systems, including solar systems, include energy storage, critical load control, backup power, and other advanced features.

Competitive advantages come from patented technologies, and system engineering expertise.

CLEAN POWER, MADE SIMPLE.

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Company Timeline

- **2001**: Princeton University spin-out
- **2002 – 2007:** R&D programs with NASA, DOE, ONR, Navsea, Army, NJ BPU, private clients
- **2008**: Hybrid (wind, solar, battery) systems installed in Bermuda, Virginia, California, New Jersey
- **2009**: GTIB 480-100 UL 1741 listing, "Green Product of the Year" Award, $3.3M NJ-sponsored investment in manufacturing plant begins
- **2010:** Military VSD deployments on the Gerald Ford Aircraft Carrier
- **2011:** ~3MW GTIB's deployed, new production facility opened with 12 MW capacity, Demand Response Inverter final pre-production testing

The Princeton Power Team

Management Team

Dr. Marshall Cohen
President & CEO
- Ph.D. Physics
- 35 years experience in solar and optoelectronics
- Co-founder and last CEO of Sensors Unlimited

Darren Hammell
Co-founder, EVP Business Development
- BSE Computer Science, Princeton University
- CEO of PPS 2001–2009
- NJBiz 40-under-40 Business Leaders

Mark Holveck
Chief Technical Officer

Paul Heavener
Engineering Manager

Rich Jaccard, PE
Production Manager

Mike Yam
Finance Administrator

Cynthia Rosen, MBA
Administration / HR

Board of Directors

Dr. Ed Zschau (Chairman)
- Congressman, California's 12th District (Silicon Valley)
- Former CEO Systems Industries, General Manager IBM
- Professor of Entrepreneurship at Princeton University

Dr. Greg Olsen
- Co-founder and CEO of Sensors Unlimited, Epitaxx
- 3rd private astronaut

Stephen Morgan
- Former President, CEO, and Chairman of the Board of Jersey Central Power and Light
- More than 30 years industry experience in all aspects of energy generation and delivery

Dr. Joseph Stach
- Former Executive Director of Massachusetts Technology Collaborative
- CEO of RF Power in Voorhees, NJ

Dr. Chris Dries
- Princeton PhD in Electronics
- President & CEO of United Silicon Carbide

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Talent. Experience. Commitment.

Sample Projects

- **Princeton Power Systems Facility: Princeton, NJ**
  - 200 kW / 164 kWh lithium-ion
  - Multi-functional Demonstration, grid-tied and backup
- **'Earth Day' PHEV Chicago, IL**
  - 100 kW / 26 kWh lithium-ion
  - PHEV Charging Station, grid-tied storage
- **U.S. Army Forward Operating Base**
  - 100kW Solar Configuration, 100kW deep-cycle lead-acid
  - Field-deployed microgrid
- **Alcatraz Island, National Park Service (Q3 2011)**
  - 400 kW Solar, 400 kW Deka Unigy AGM batteries, twin 400kW Diesel GenSets
  - 'Standalone Controller' for microgrid operation
- **Bermuda Electric Light Company (BELCO)**
  - Wind, solar, battery system deployed in Bermuda, lead-acid

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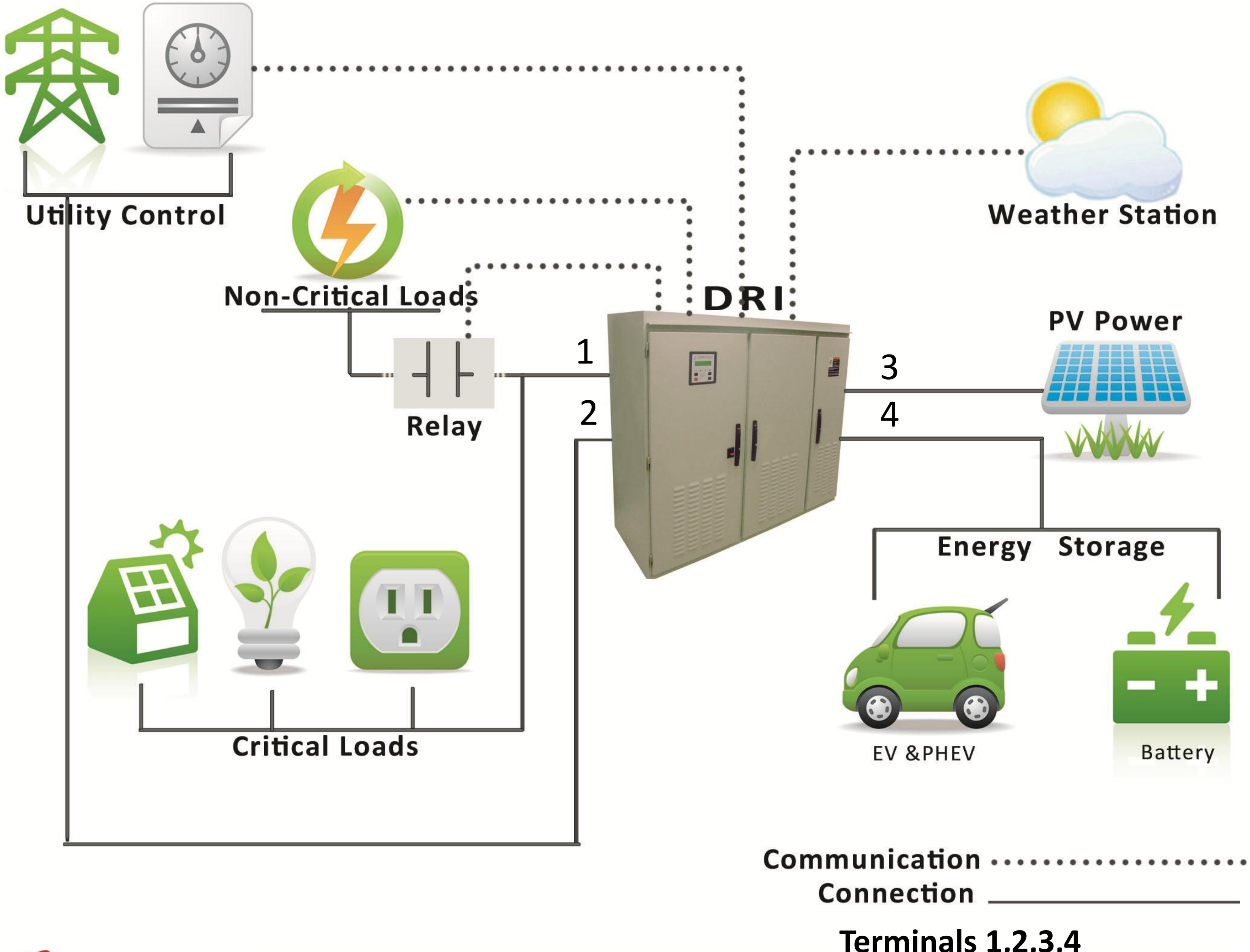
Demand Response Inverter Concept



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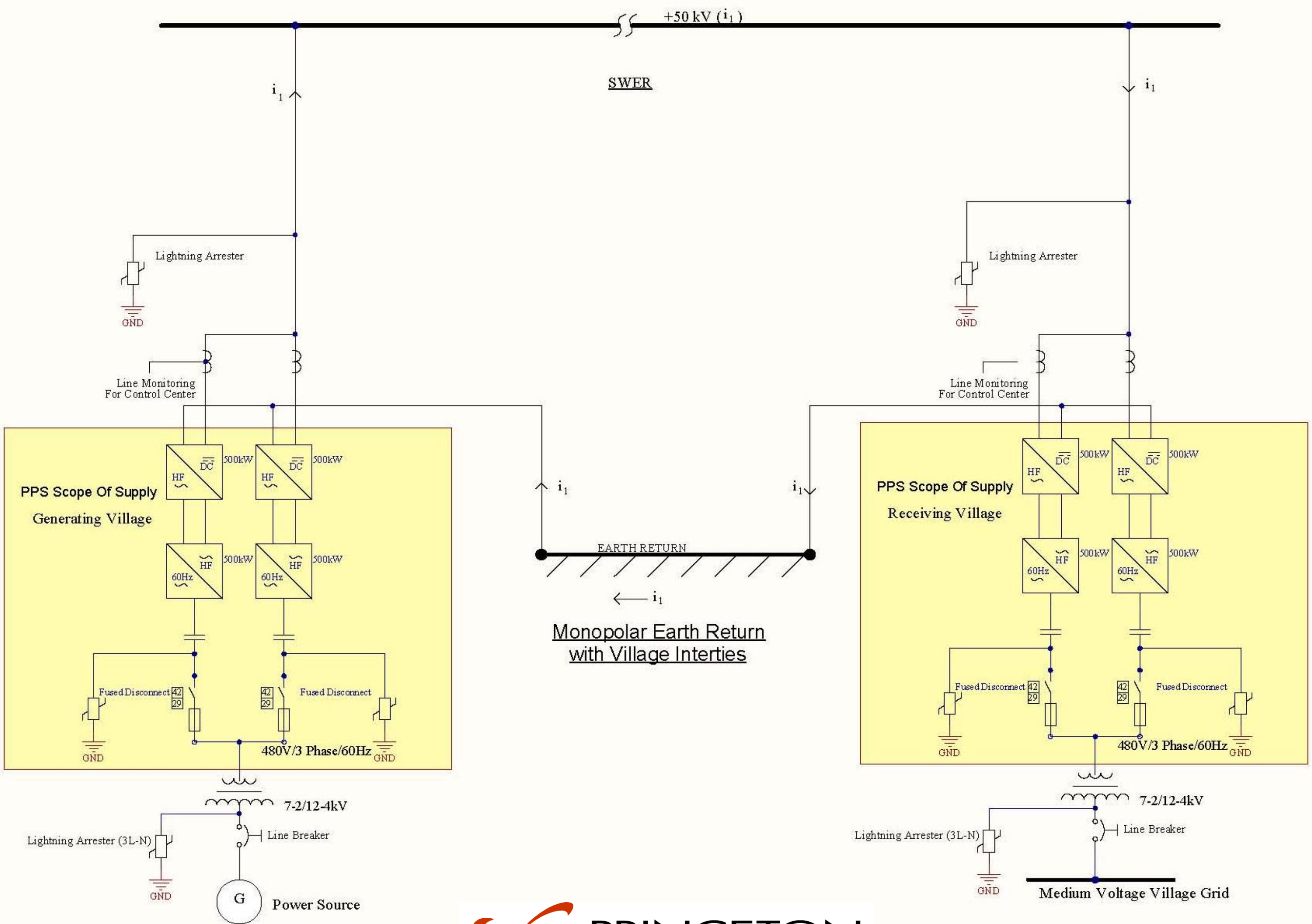
HVDC Power Converter Background

- The HVDC power converter changes low-voltage alternating current (LVAC) power to high-voltage direct current (HVDC) to allow efficient power transmission between communities, and usable power within the community
- The HVDC Power Converter plays a key roll in reducing transmission costs and increasing grid reliability for remote and isolated electrical systems
- The HVDC power converter has been a ‘missing link’ in realizing the HVDC Transmission concept
- PPS’ HVDC converter, partially funded through PolarConsult, is a 500 kW power converter, capable of parallel operation to 10 MW or more, and bi-directional power conversion between three-phase 480 VAC and 50 kVDC.

1MW Transmission Line Diagram



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Power Converter Components

Low-Voltage Enclosure
(480 VAC ←→ 6-8 kHz 800 VAC)

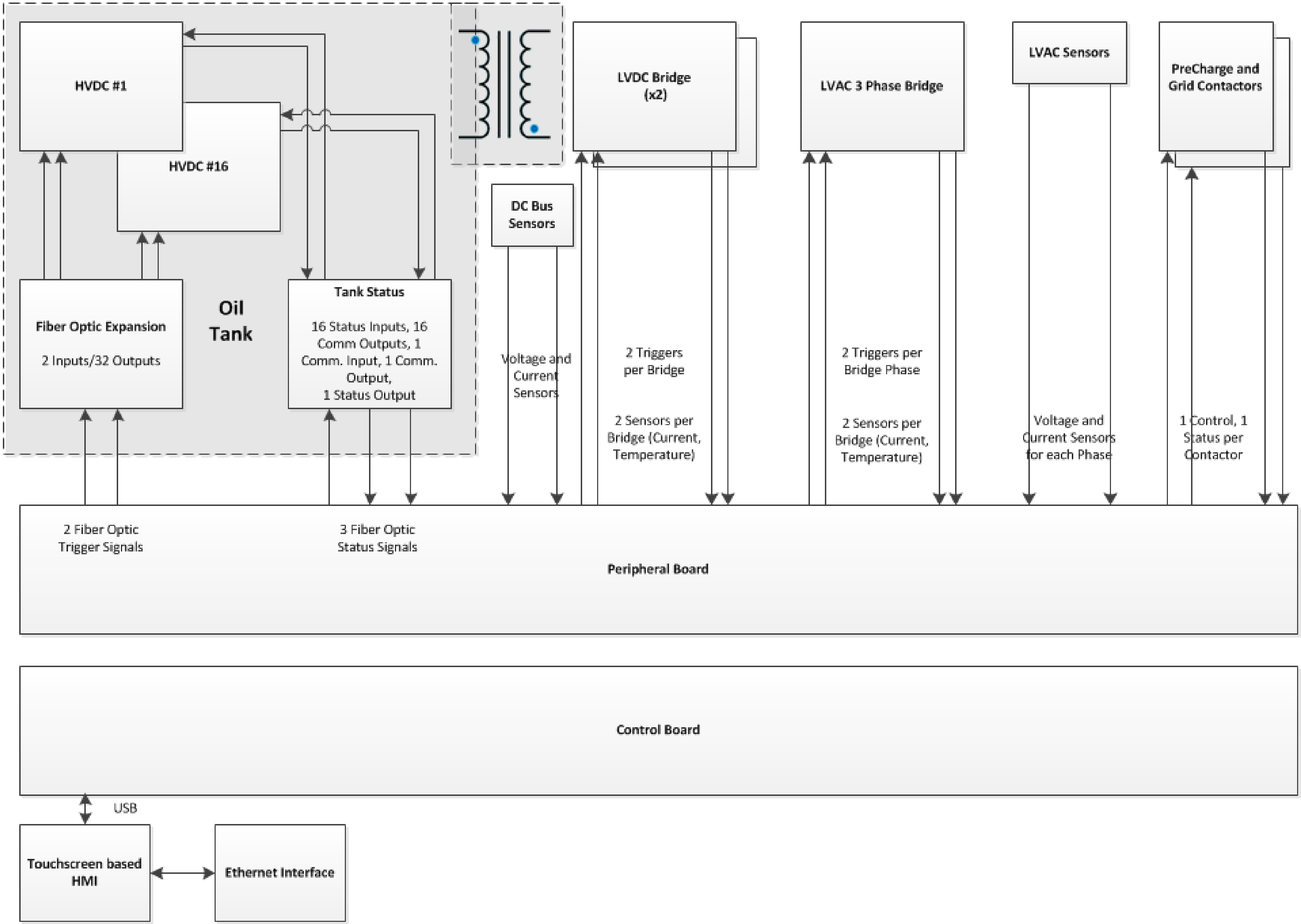
High-Voltage Enclosure
(800 VAC ←→ 50 kVDC)
Includes xformer in oil

HV Enclosure LV Enclosure

Phased Development Summary

- In Phase I, a design was completed and a bench-scale concept and feasibility unit was constructed, and concept validation testing performed (December 2007 – February 2009)
- In this Phase II, 2 500kW prototype units are being built and tested
  - Contractual PoP: May 2010 – October 2011
  - PPS will work through December 2011 to complete Testing
- A Phase II technology demonstration is scheduled for November 14th 2011, at Princeton Power Systems High Voltage Testing Facility in Princeton, NJ.

500 kW Module – Controls Block Diagram



Phase II Status Summary

- Previously Completed Milestones

- Schedule for Completion of Phase II

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Phase II Task Status

Task	Percent Complete
2.1 Develop Converter Voltage Standards	
2.1.1 Review Voltage Stds with PCA and AVEC	100%
2.1.2 Review Safety Packaging & Perf. Req. with PCA & AVEC	100%
2.1.3 Review Power Line Comm System	100%
2.1.4 Develop System Spec for 1MW and Sign off w/PCA	100%
2.2 Converter Design and Construction	
2.2.1 Modify PE and Circuit Topology (Procurement Spec)	100%
2.2.2 Perform Computer Modeling	100%
2.2.3 Reliability / failure analysis of HVDC Converter Design	100%
2.2.4 Modify Control Software	100%
2.2.5 Evaluate and Mod design to diagnose faults/failures	100%
2.2.6 Develop Thermal Managemement System	100%
2.2.7 Generate Mech Design (HVDC System)	100%
2.2.8 Generate 3D Model and Detailed Metalwork Fab Dwgs	100%
2.2.9 Identify / Develop Vendor / Procurement	100%
2.2.10 Assemble (1) 1MW Unit	95%
2.3 Converter Test Plan	
2.3.1 Develop Converter Test Plan	100%
2.3.2 Review and Appr of Test Plan by ACEP	0%
2.3.3 Test Plan Revisions	0%
2.4 Converter Testing and Reporting	
2.4.1 Di-electric Test	80%
2.4.2 Various failure mode response testing	50%
2.4.3 Operational / Funtional Testing	50%
2.4.4 Efficiency Testing	30%
2.4.5 Temperature Rise Testing	20%
2.4.6 Test Report	0%

Completed Milestones

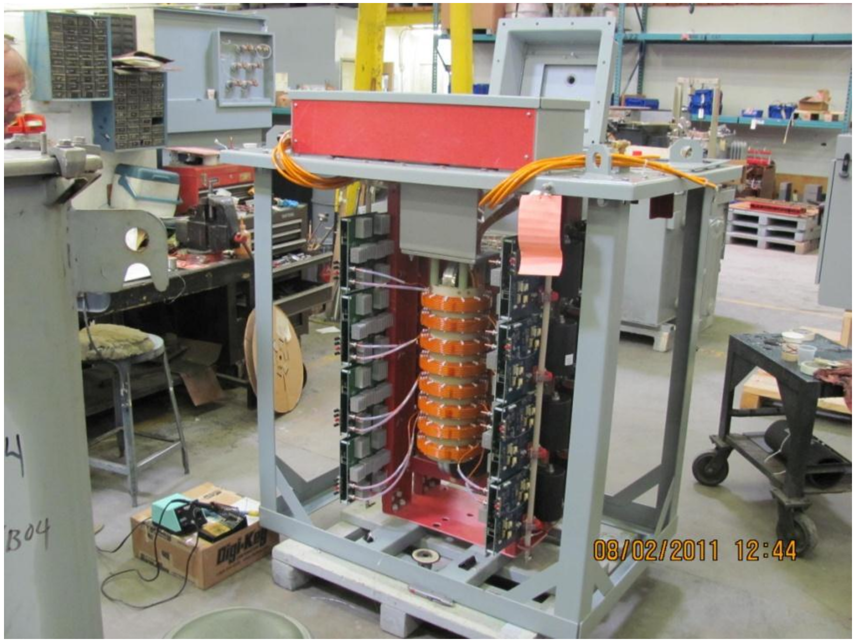
- Air Testing Completed on Transformer assembly #1.
  - Issues with design exposed during Hi-Pot test.
  - Changes Implemented, 20kV Hi-Pot test Passed.
- Transformer #1 immersed in oil
  - Hi-Pot 70kV Test Passed
- Implemented design changes to Transformer #2.
  - Transformer #2 20kV Hi-Pot Test Passed.
- LV Enclosure #1 assembly complete.
  - Functional testing completed
- LV Enclosure #2 assembly complete.

Transformer and HV Stacks

Completed:

Assembly of Module #1 completed, Hi-Pot tested in air to 15kV

Operational Testing to 9kV



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HV Transformer #1

Transformer #1 immersed in oil tank for in-oil testing

Controls Sub-Assembly Testing

Component Tests Completed

- Tank Status Board
  - Fiber Optic assembly
  - FPGA Configuration
  - Individual Circuit tests
    - Sensor inputs
    - Status output
    - UART input/output

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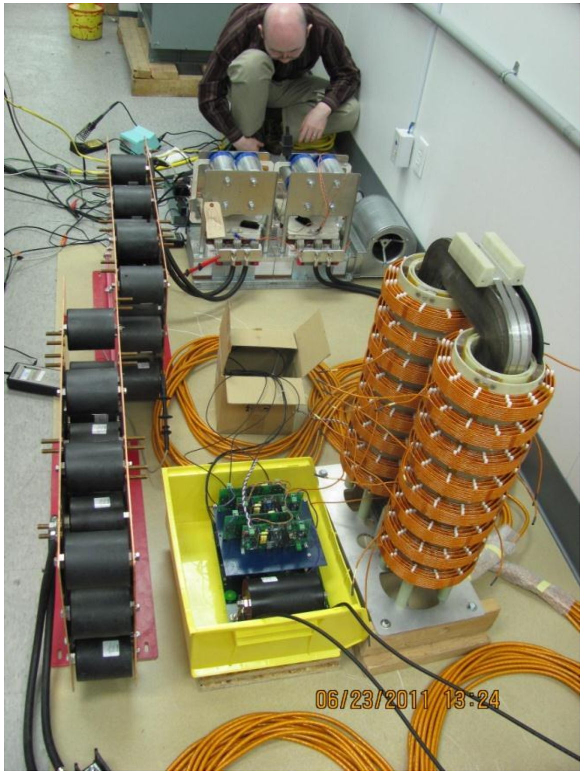
Controls Sub-Assembly Testing

Component Tests Completed

- Peripheral board
  - Trigger Tests
  - Sensor Tests
  - Fiber Optic Tests
- Simulated system test of the Tank Status board
- DSP software coding and modification
  - Software start up
    - Initialization
    - Calibration
- Basic peripheral control and monitoring



Current Status

500kW Module 1

HVDC Transformer and LVAC Enclosure Installed in PPS HV Test Lab for HV Bring Up

500kW Module 2

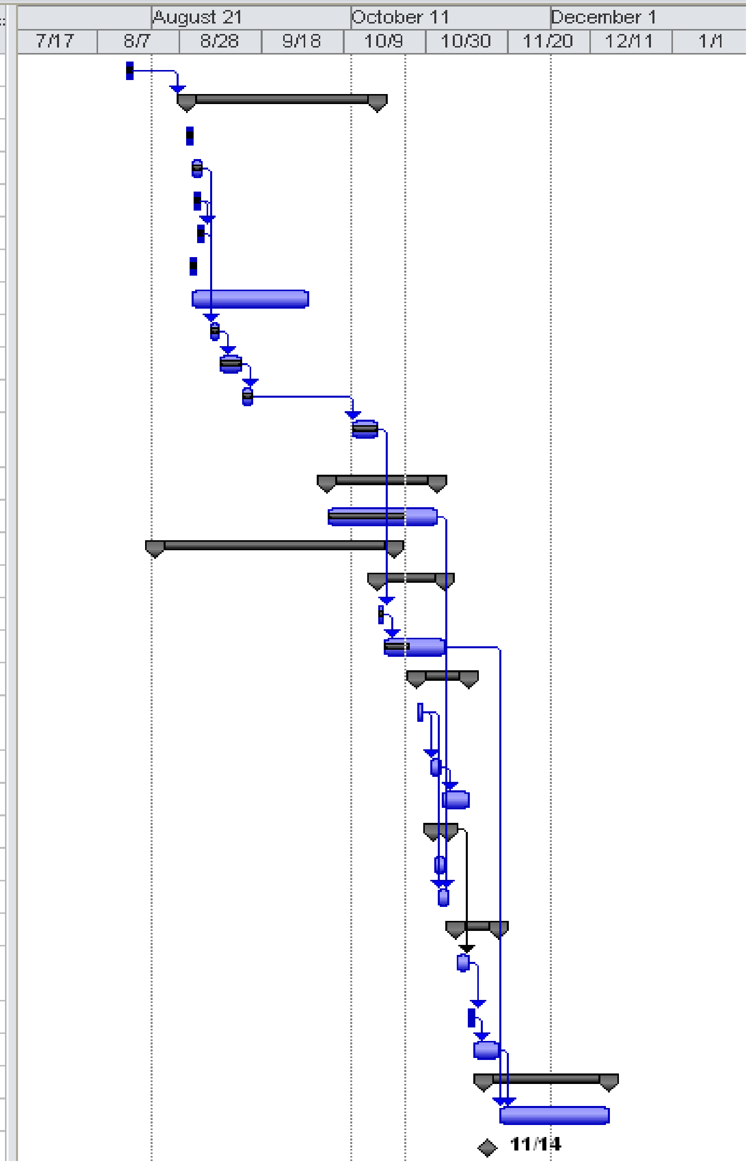
Transformer Tank awaiting in air testing completion

Transformer HV Assy ready for In Air testing 10-28

LVAC Unit completed at PPS HV Lab

Schedule for Completion of Remaining Phase II Tasks as of 10/25/2011

	i	Task Name	Duration	Start	Finish	Predecessors
2	✓	System #1 Hi-Pot Testing	1 day	Mon 8/15/11	Mon 8/15/11	
3		**System #1 Bring Up in Air**	**35 days?**	**Tue 8/30/11**	**Mon 10/17/11**	2
4	✓	Re install BNC's 90 deg.	1 day?	Tue 8/30/11	Tue 8/30/11	
5	✓	Repair 2 Trigger Bds	3 days	Wed 8/31/11	Fri 9/2/11	
6	✓	Rework Transformer more Kapton	1 day?	Thu 9/1/11	Thu 9/1/11	
7	✓	Hi Pot Transformer	1 day?	Fri 9/2/11	Fri 9/2/11	6
8	✓	Integrate IGBT Temp Sensors	1 day?	Wed 8/31/11	Wed 8/31/11	
9		Power Supply Switcher Bd	22 days	Wed 8/31/11	Thu 9/29/11	
10	✓	AC to DC Test	2 days	Mon 9/5/11	Tue 9/6/11	5,6,7
11	✓	DC to AC Switching Test	4 days	Wed 9/7/11	Mon 9/12/11	10
12	✓	Final Verification	3 days	Tue 9/13/11	Thu 9/15/11	11
13	✓	Tank #1 Transformer Insert to NWL for Oil Processing	5 days	Tue 10/11/11	Mon 10/17/11	12
14		**System #1 LV Controls Bring up**	**20 days**	**Wed 10/5/11**	**Tue 11/1/11**	
15		Control Bd DSP Code	20 days	Wed 10/5/11	Tue 11/1/11	
16	✓	**System #2 Kit for NWL**	**45 days?**	**Mon 8/22/11**	**Fri 10/21/11**	
23		**System #1 HV Testing at 3175**	**13 days?**	**Tue 10/18/11**	**Thu 11/3/11**	
24	✓	Tank #1 Returned Processed	1 day?	Tue 10/18/11	Tue 10/18/11	13
25		System #1 HV Bring Up	12 days	Wed 10/19/11	Thu 11/3/11	24
26		**System #2 Bring Up in Air**	**9 days?**	**Fri 10/28/11**	**Wed 11/9/11**	
27		Tank Insert # 2 Returned to PPS for Dry Testing	1 day?	Fri 10/28/11	Fri 10/28/11	22
28		System #2 Hi-Pot Testing	3 days	Mon 10/31/11	Wed 11/2/11	27
29		System #2 Bring Up in Air	5 days	Thu 11/3/11	Wed 11/9/11	28
30		**System #2 LV Controls Bring Up**	**4 days**	**Tue 11/1/11**	**Fri 11/4/11**	22
31		Bring Up LV Enclosure #2	3 days	Tue 11/1/11	Thu 11/3/11	
32		Bring Up and Verify	3 days	Wed 11/2/11	Fri 11/4/11	15,27
33		**System #2 HV Testing at 3175**	**9 days?**	**Mon 11/7/11**	**Thu 11/17/11**	
34		Tank #2 Transformer insert to NWL for Processing in Oil	3 days	Mon 11/7/11	Wed 11/9/11	30
35		Tank #2 Returned to PPS Processed	1 day?	Thu 11/10/11	Thu 11/10/11	34
36		System #2 HV Bring Up	5 days	Fri 11/11/11	Thu 11/17/11	35
37		**System HV Testing**	**24 days?**	**Mon 11/14/11**	**Thu 12/15/11**	
38		HV System Testing	20 days	Fri 11/18/11	Thu 12/15/11	25,36
39		Technology Demonstration	1 day?	Mon 11/14/11	Mon 11/14/11	



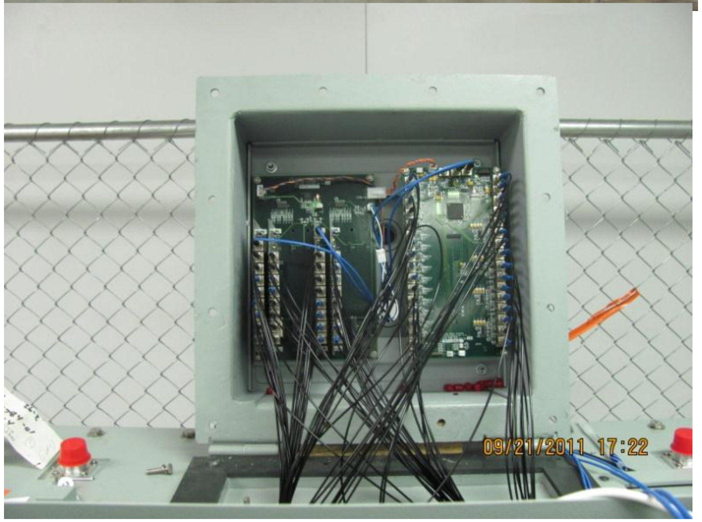
Phase II Remaining Tasks

- LV Enclosure #1 with Transformer #1 Operational Testing to 50kV underway
- Transformer #2 assembly ready for Air Testing. 10-28
- LV Enclosure #2 Operational Testing underway
- Transformer #2 immersed in oil 11-7
- LV Enclosure #2 with Transformer #2 Operational Testing to 50kV 11-17
- Dual-module System Testing 11-17 to 12-15

“Module 1” HV Testing

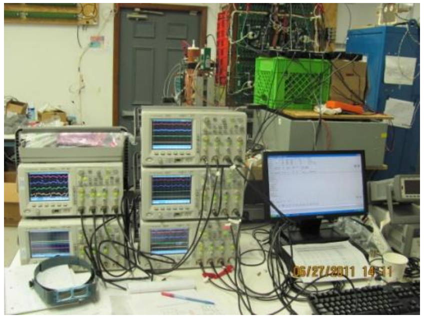
- **Module Integration (Underway)**

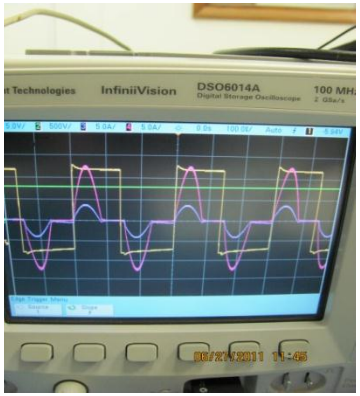
- Visual inspection
  - Tank:
    - Electrical / Mechanical
  - LV Enclosure:
    - Electrical /Mechanical
- Hi-Pot
  - Tank
    - Across transformer, 71 kV
    - DC to ground
    - AC to ground
  - LV Enclosure
    - (DC and AC) to ground



“Module 1” HV Testing

- **Controls Operational Testing (Underway)**





- Control power
- Communication interfaces
- Sensor input
- System I/O
- User I/O
- Triggering check
  - Check trigger lines for basic operation
  - Characterize propagation delay and skew between electrical and optical transmission lines, and correct if necessary.
  - Switch power using a test pattern and LVLE (Low voltage, Limited Energy) power source to confirm correct ability to switch at frequency, with dead time etc.

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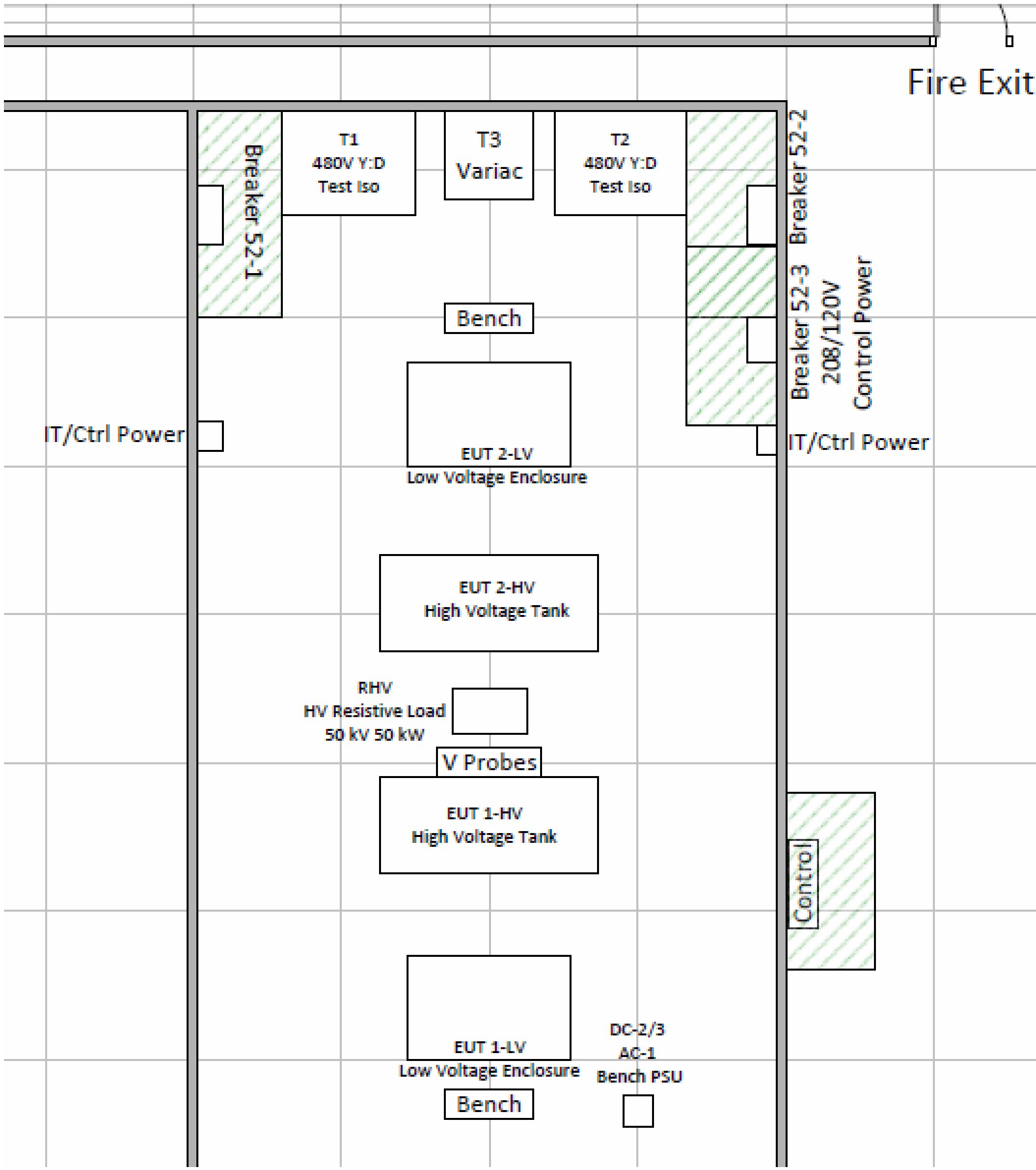
1MW Dual-module System Testing

- Functional tests
  - Rated voltage test- 50kV DC using earth return
    - 3 phase 480 VAC to 50 kVDC
    - 50 kVDC to 3 phase 480 VAC
  - Power sharing between parallel systems
- Efficiency test @ several power levels
- Temperature rise test @ rated current and low voltage

HV Facility Layout



NOTES

NESC Table 124.1 Clearances:

Vertical	9'6"-10"
Horizontal	4'- 4'4"
Guard	1'4"

Facility available S.C. current

Air Testing Configuration

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Summary of Key Performance Metrics

Phase II Converter Materials Costs

	BOM Summary	10pcs.	100pcs.
1MW Power Converter System	Power Electronics	$116K	$100K
	Controls & Monitoring	$32K	$26K
	Mechanical- BOS	$69K	$56K
	Total Parts Cost 1MW	$217K	$182K

We have a $250/kW cost target for a 'commercial production' unit in low-medium volumes

'Commercial Production' means that substantial work has been done to take the functional Phase II prototype and perform thorough testing and manufacturing engineering to reduce costs. This will require additional work for testing and design refinement/cost reduction.

This additional work accounts for achieving $250/kW based on the actual numbers from Phase II.

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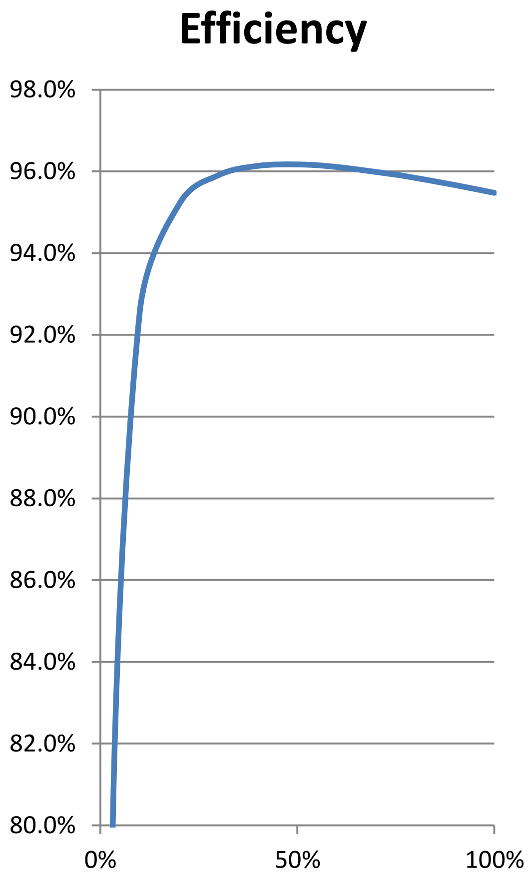
Phase II Converter Efficiency

Total Full-Power Loss Calculation

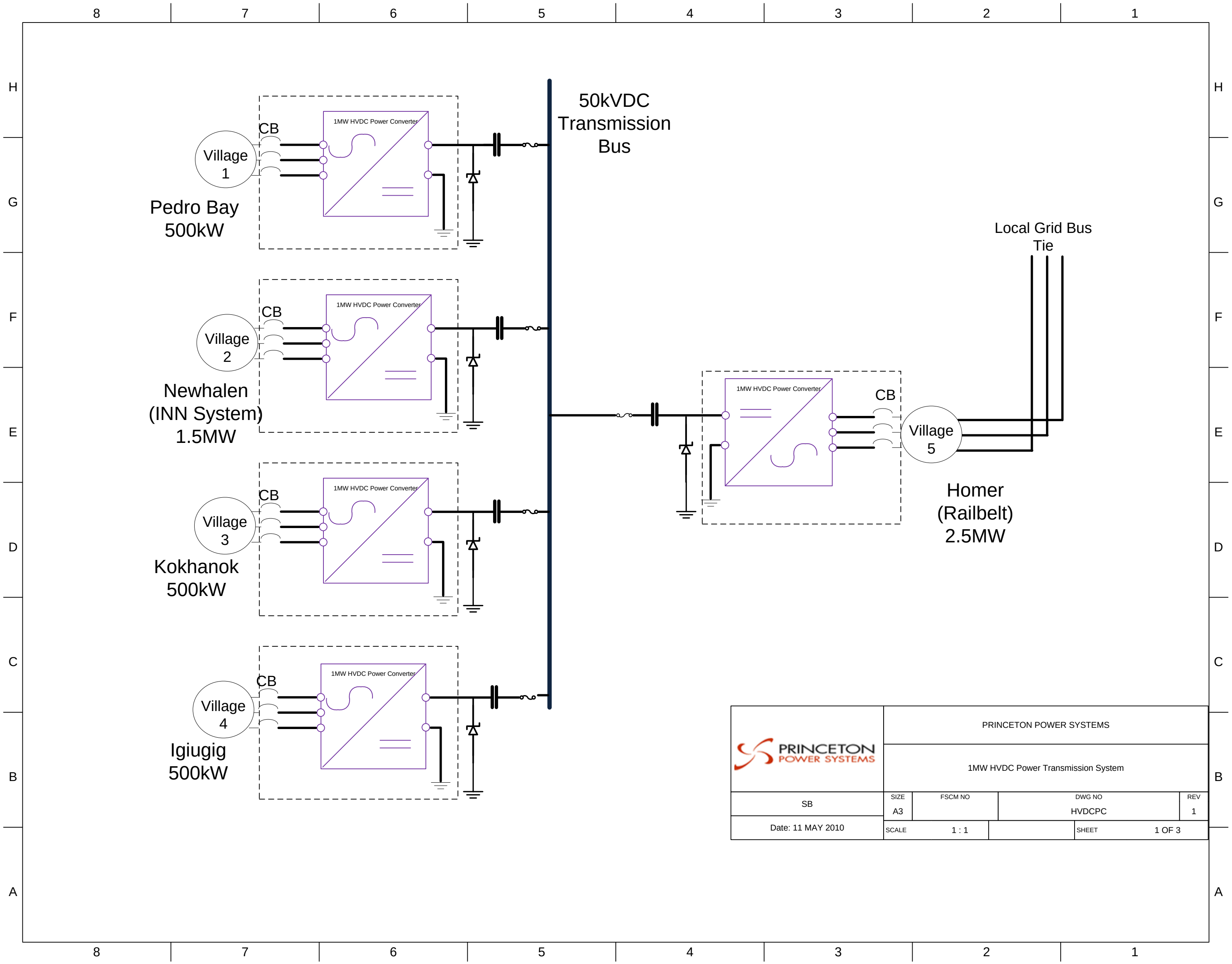
Component	RMS	Linear	Fixed	sum	%
Parasitic	500	500	500	1500	0.300%
HVDC Bridge :	979	2774	3	3756	0.751%
HF Transformer :	716	0	1300	2016	0.403%
HF Capacitors :	226	0	0	226	0.045%
HV Stack 50kV Balancing:	0	0	781	781	0.156%
HV Stack 24V Balancing:	0	0	150	150	0.030%
LVDC Bridge :	1349	0	0	1349	0.270%
LVAC Bridge :	7224	2382	0	9606	1.921%
AC Filter Inductor (L1) :	755		113	868	0.174%
AC Filter Capacitor (Cac) :	150			150	0.030%
Grid Inductor (L2) :	748			748	0.150%
Control System :		100	50	150	0.030%
Cooling System :		826		826	0.165%
Wireing & Bus Bar :	100	400		500	0.100%
Total	**12747**	**6982**	**2897**	**22627**	**4.525%**

Converter Efficiency w/aux losses

Power %	RMS loss	Linear Loss	Fixed loss	Total Loss	Efficiency
1%	1.3	69.8	2897.4	2968.5	40.6%
3%	11.5	209.5	2897.4	3118.3	79.2%
10%	127.5	698.2	2897.4	3723.1	92.6%
20%	509.9	1396.4	2897.4	4803.7	95.2%
30%	1147.3	2094.6	2897.4	6139.3	95.9%
40%	2039.6	2792.8	2897.4	7729.8	96.1%
50%	3186.9	3491.0	2897.4	9575.3	96.2%
60%	4589.1	4189.2	2897.4	11675.7	96.1%
75%	7170.4	5236.5	2897.4	15304.3	95.9%
80%	8158.3	5585.6	2897.4	16641.3	95.8%
90%	10325.4	6283.8	2897.4	19506.6	95.7%
100%	12747.4	6982.0	2897.4	22626.8	95.5%



Possible System Application



Beyond Phase II

- The Phase II project includes the following: Dielectric test, Basic failure mode response testing, Basic Operational / Functional testing, Efficiency testing at various power levels, and temperature rise testing at rated current and low voltage.
- We anticipate that the following testing will be required to prepare the 500kW HVDC units for deployment in a commercial setting:
  - Detailed Failure Mode Response Testing.
  - Thorough Operational and Functional Testing.
  - Confidence Testing including load and endurance tests.
  - Design review and modifications based on test results.

Beyond Phase II

- Documentation including Operations Manual.
- Training for Utility Team, Installation and Commissioning.
- On-site support for Installation and Commissioning.
- Site development
  - General Electrical Design
  - Protective Relay Design
  - System Dielectric Coordination
  - Communications System Design
  - Structure / Container Design
- PPS recommends having spare modules and components that may be required throughout this phase.
- It is anticipated that this phase would require 8-10 Months and cost between $600k and $800k

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