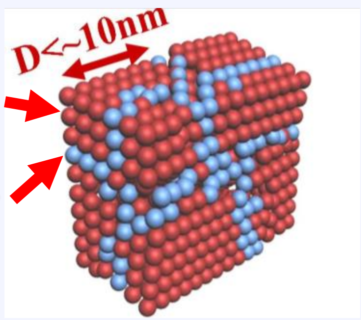
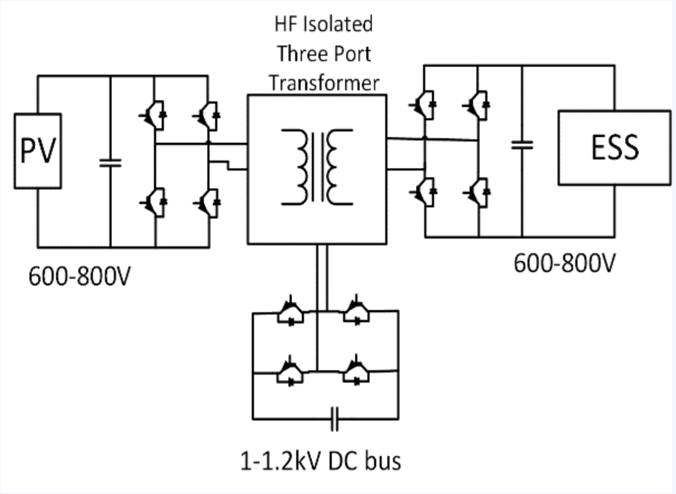
Combined PV / Battery Grid Integration with High Frequency Magnetics Enabled Power Electronics

National Energy Technology Laboratory

SuNLaMP Award # DE-EE00031004

Phase 1 – Quarter 3





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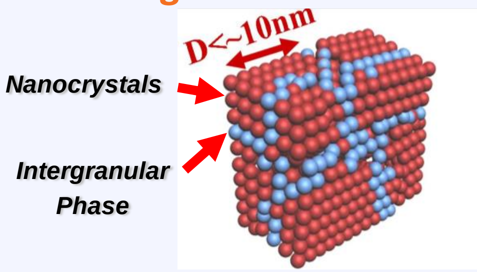
Project Overview : Teaming Structure

Nanocomposite

Soft Magnets

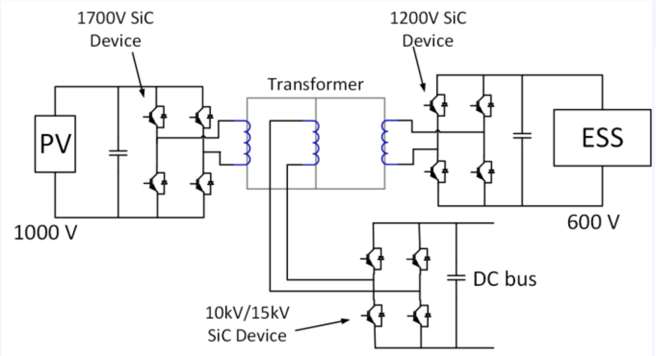


3-Winding Nanocomposite

Core Transformer

Three Port Modular

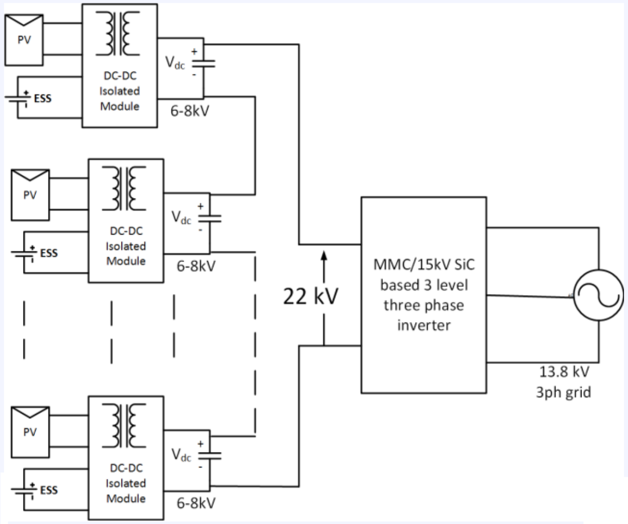
DC-DC Converter



High Frequency Magnetics

+ Wide Bandgap Semiconductors

Overall PV / ES Inverter System

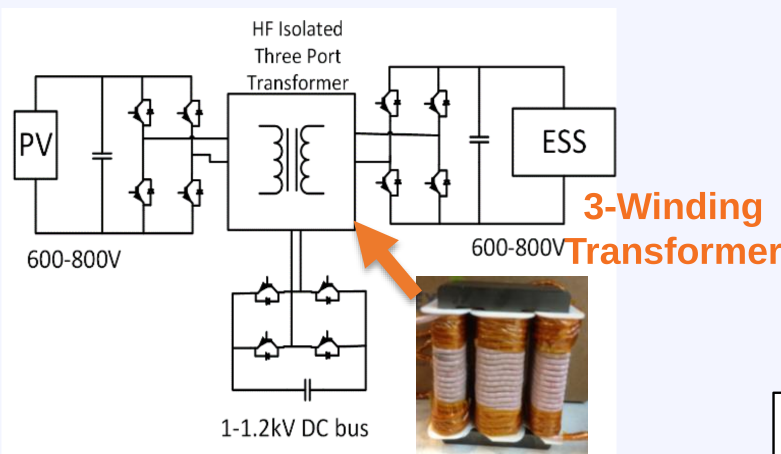


- Team Structure Spans National Labs, Industry, and Universities
- Modular MW-Scale Inverter for Combined Photovoltaic and Energy Storage

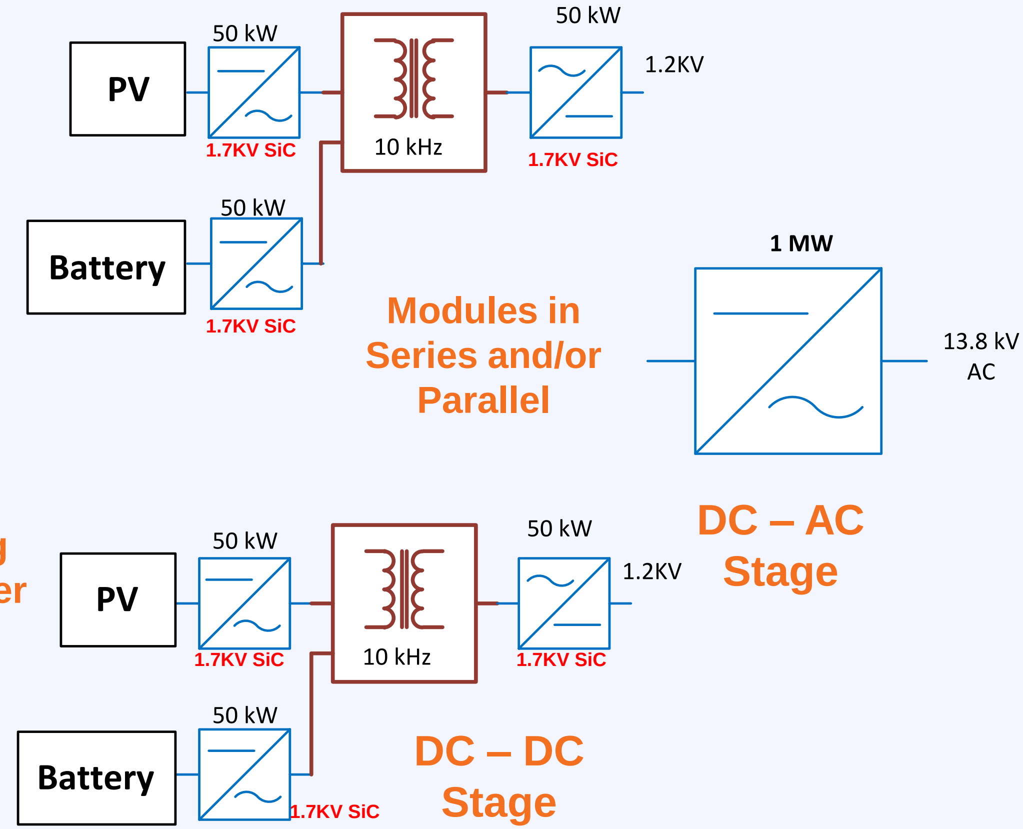
Project Overview : Proposed Converter Topology

New Enabled Use Case

	PV / ES Charging and Discharging Scenarios	
#1	PV Delivering Maximum Power	ES Charging from PV
#2	PV Delivering Maximum Power	ES Charging from Grid
#3	PV Delivering Maximum Power	ES Discharging to Grid
#4	PV Delivering Reduced (or Zero) Power	ES Charging from Grid
#5	PV Delivering Reduced (or Zero) Power	ES Discharging to Grid
#6	PV Delivering Maximum or Reduced Power	ES Idle (Not Charging or Discharging)



Integrated DC-DC Converter Modules



- Combined Solar PV and Energy Storage Integration with DC-DC Converters
- Coupling Through a Three Winding High Frequency Transformer Core
- Grid Interconnection Through a DC / AC Inverter Stage

Project Overview : Task Structure

- Task 1: Detailed Converter Component / Architecture Definition
- Task 2 : DC-DC Integrated Converter Modules
- Task 3 : System Level Integration Simulation and Experimental Demonstration
- Task 4: Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

A Particular Emphasis is Placed on Enabling Magnetics Technology: Alloy Development and High Frequency Core and Transformer Design

Primary Project Milestones and Deliverables

- Commercialization Plans for the Power Electronics and HF Transformer Technologies and Enabling Magnetics
- Design and Prototype of a 50kW DC-DC Converter Module for Combined Photovoltaic and Energy Storage Integration
- Successful Demonstration of 2 x 50kW Converter Modules to 60Hz AC Grid Interconnection
- Successful Demonstration of Advanced Enabling Magnetics
  - Engineered Permeability Cores Using Advanced Processing
  - Advanced Nanocomposite Based High Frequency Transformers

Quantitative System Metrics for Converter Topology

- Capital Cost < \$0.1 / W (Proposed Modification to \$0.15/W)
- Overall Efficiency > 98%
- Power Density > 8 W / in^3 (~2x current Eaton solar inverters)
- Pathway to Reliability > 25 Year Lifetime (Estimated MTBF)
- Satisfying all Necessary Interconnection Standards Including IEEE 1547 and UL 1741

Metrics for the Proposed Converter Topology are Aligned with SunShot Initiative Metrics Modified Slightly for Combined PV / ES

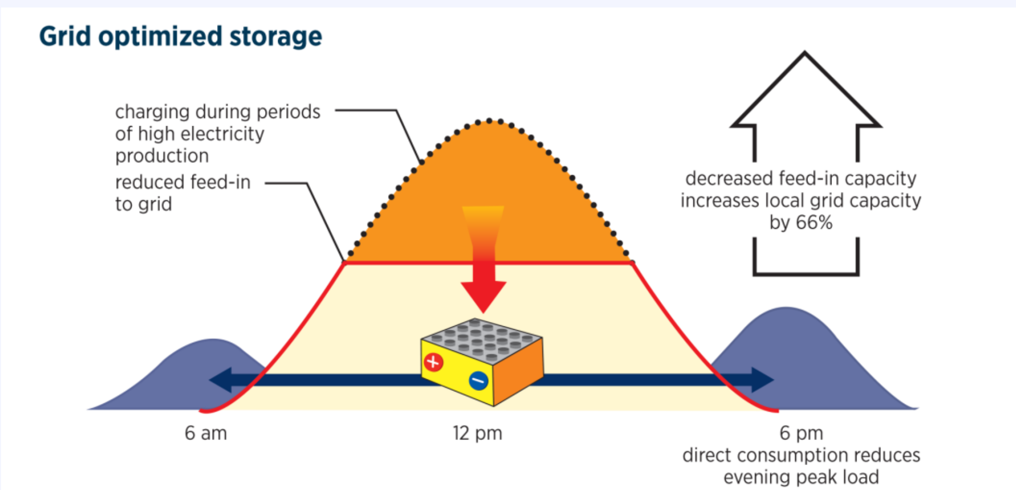
Task 1: Detailed Converter Component / Architecture Definition

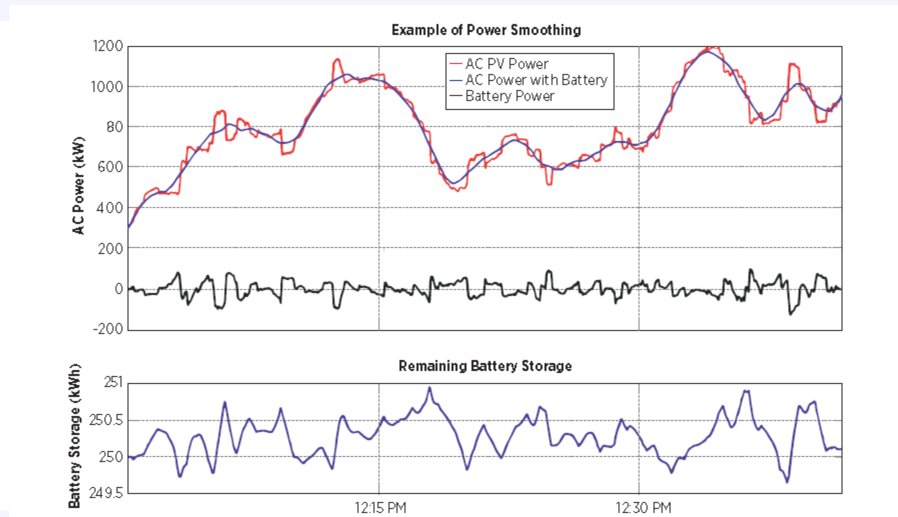
- Energy Time Shift → Approximate by Constant Average Power Delivery
- Renewable Energy Smoothing → Not Quantified (System Level Benefit)
- Increased Energy Output at Fixed DC / AC Inverter Stage Rating
- <u>Higher Efficiency PV Energy Local Consumption (Reduced Conversion Steps)</u>

Not Quantified Here

Secondary

Primary





Key Value Propositions Have Been Identified for <u>Combined Solar PV and Energy Storage on the DC Side</u> for Benchmarking

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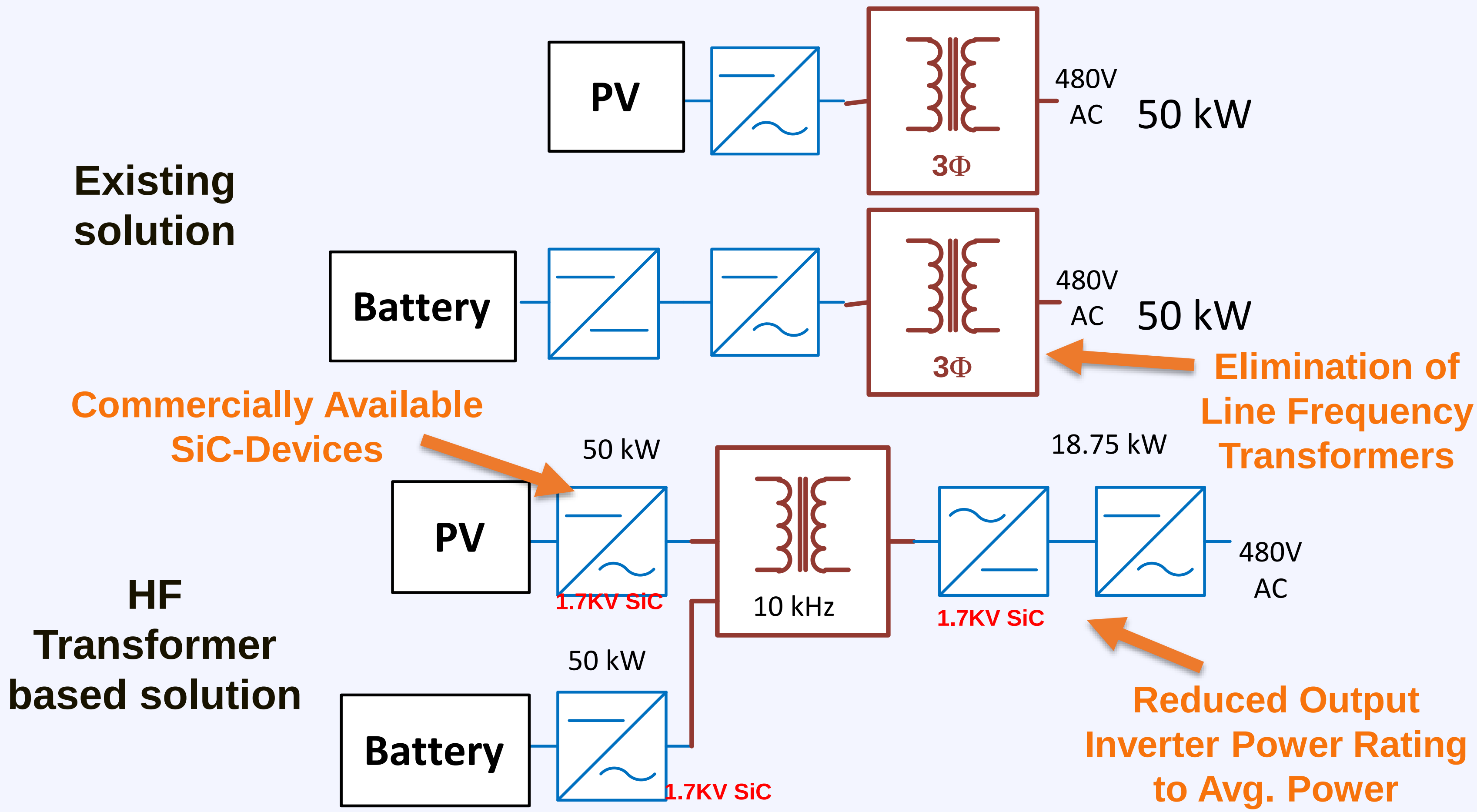
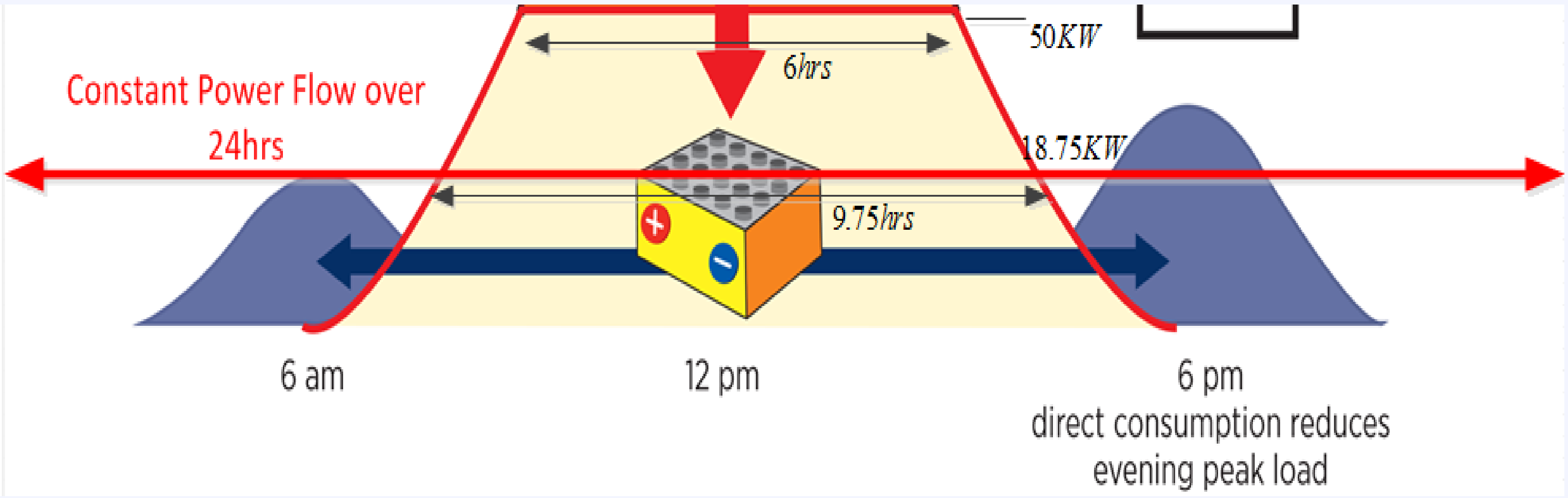
<u>* See Assumptions in Appendix Slides for Architecture Studies</u>

Task 1: Detailed Converter Component / Architecture Definition



Commercial Scale: Established Base Case and Proposed HF Transformer Solution (50kW, 480Vac)

Task 1: Detailed Converter Component / Architecture Definition



- Assumptions:
  - Constant power over 24 hours
  - Battery capacity is high enough to maintain
  - Day-time PV array output power is close to trapezoid with 50kW peak power
- <u>New solution has 99% battery charging efficiency, versus traditional solution is only 94%.</u>

- Energy saving per day: 12.3KWh
- Dollar saving per year: $225 ($0.05/W electric price)
- Return on initial investment: 2.23 years
- Lifetime earning of 25 years: $5.1K

Task 1: Detailed Converter Component / Architecture Definition

Architectures	Efficiency (PV to 480Vac)	Efficiency (PV to Battery)	Converter + Transformer Material Cost/W**	Power Density	Lifetime Saving	Reliability (MTBF)
Existing Solution (AC Coupled)	97-98%	**93-95%**	$0.30/W	8.4 KW/m^3	-	40.3 years
HF Transformer Solution (DC Coupled)	98%	**99%**	$0.295/W	114.1 KW/m^3	$5.6K	83.8 years

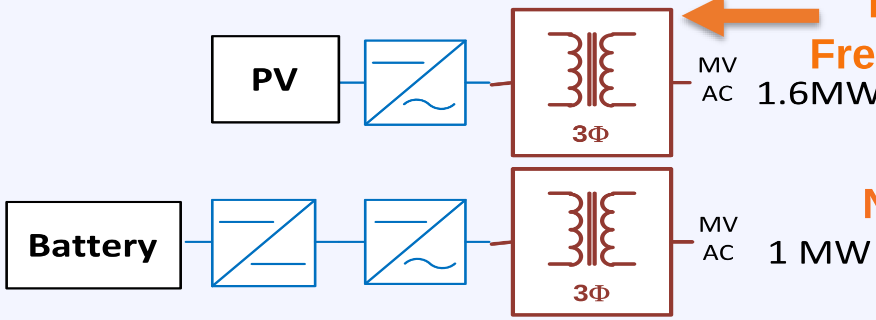
- Higher efficiency from PV to battery/load (local energy consumption)
  - $224/W saving per year
  - 2.2 years cover the initial cost difference
  - Total lifetime earning $5K
- 8+ times higher power density
- Twice MTBF of the conventional solution

Proposed Topology is Attractive at Commercial Scale.

Commercially Available SiC-Devices and HF Magnetics.

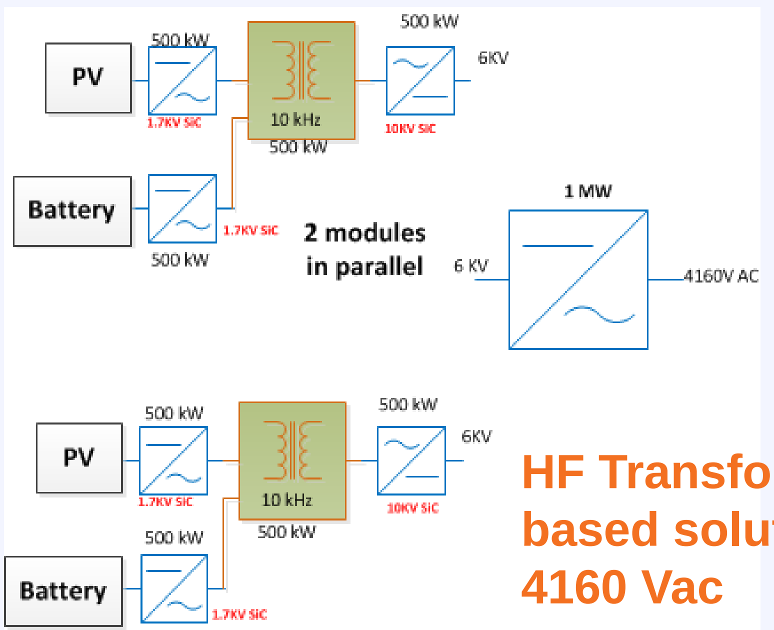
Task 1: Detailed Converter Component / Architecture Definition

Existing solution

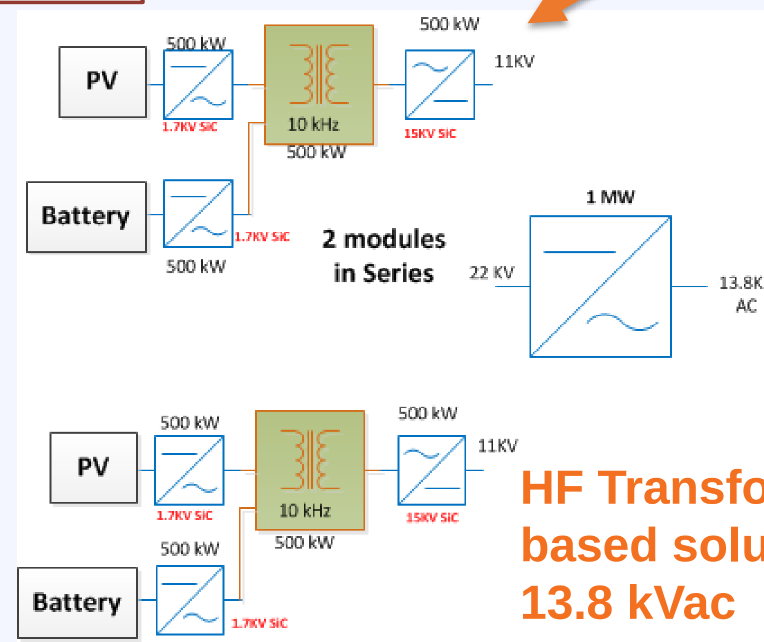


Elimination of Line Frequency Transformers

NOTE : Requires 15kV SiC – Based Devices



HF Transformer based solution – 4160 Vac



HF Transformer based solution – 13.8 kVac

Utility Scale: Base Case and HF Transformer Solution (1MW, 4160Vac or 13.8kVac, 500kW Modules)

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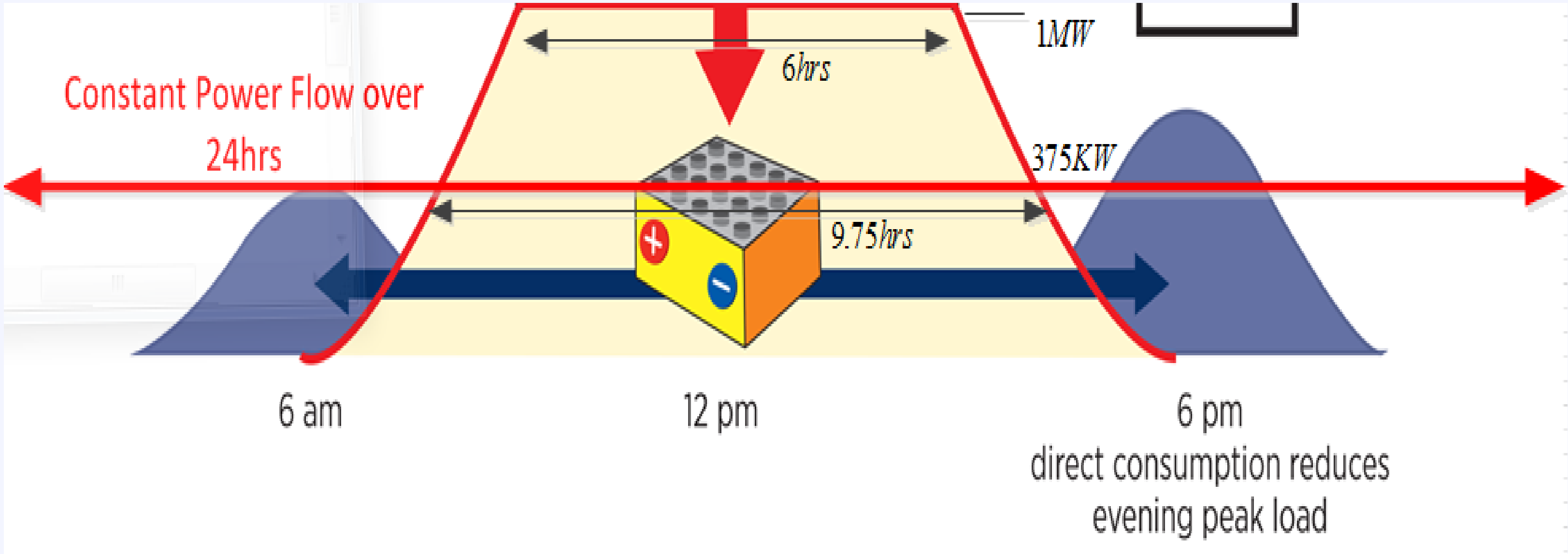
Task 1: Detailed Converter Component / Architecture Definition



- Assumptions:
  - Constant power over 24 hours
  - Battery capacity is high enough to maintain
  - Day-time PV array output power is close to trapezoid with 1MW peak power
- <u>New solution has 99% battery charging efficiency, versus traditional solution is only 94%.</u>

- Energy saving per day: 246KWh
- Dollar saving per year: $4.5k ($0.05/W electric price)
- Return on initial investment: 6.7 years
- Lifetime earning of 25 years: $82k

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Task 1: Detailed Converter Component / Architecture Definition

Architectures	Efficiency (PV to 480Vac)	Efficiency (PV to Battery)	Converter + Transformer Material Cost/W**	Power Density	Lifetime Saving	Reliability (MTBF)
Existing solution (AC Coupled)	97-98%	**93-95%**	\$0.10/W	38.9 KW/m^3	-	20.1 years
New solution	98%	<u>**99%**</u>	\$0.13/W	74.7 KW/M^3	82K	26 years

- Cost is slightly higher and competitive, <u>but REQUIRES 15kV SiC devices</u>
- ~2x times higher power density
- More reliable than the conventional solution with MBTF > 25 years
- <u>Proposed Topology Becomes More Attractive as the Reliance on Energy Storage Component Increases</u>

Task 1: Detailed Converter Component / Architecture Definition

Architectures	Efficiency (PV to 480Vac)	Efficiency (PV to Battery)	Converter + Transformer Material Cost/W**	Power Density	Lifetime Saving	Reliability (MTBF)
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Potential Pathways Towards the SunShot Initiative of $0.1 / W at Utility Scale

#1: Reduce the Inverter Output Rating to Minimum Required (~ 375kW)

#2: Reduce (or Clarify?) Costs Associated with High Frequency Transformers

Suggestion : Consider Increasing Cost Metric to $0.15 / W Due to Higher Value of Combined Solar and Energy Storage Inverter Technology

Task 1: Detailed Converter Component / Architecture Definition

Comparison of 3-Phase DC / AC Inverters for 13.8kV AC Grid Integration at 1MW

* 3 no. 15kV, 20A MOSFETs or 6 no. 10kV, 10A MOSFETs added in parallel for each switch to meet current rating requirements.

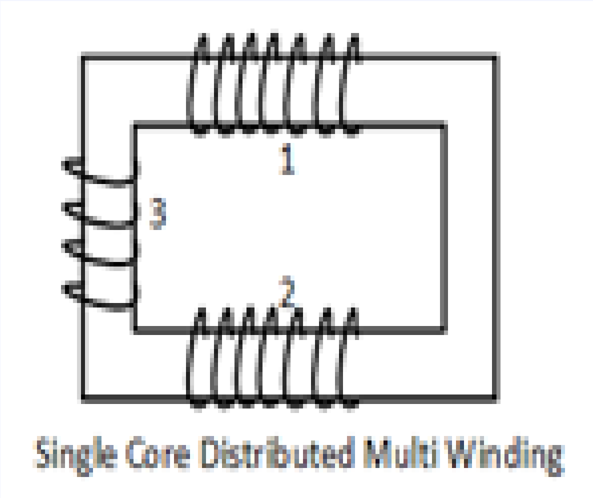
Parameters	3 Level Voltage Source Converter		Cascaded H-bridge	
	10 kV, 10 A MOSFET based Design	**15 kV, 20 A MOSFET based Design**	**10 kV, 10 A MOSFET based Design**	**15 kV, 20 A MOSFET based Design**
Device Count	144	36	144	72
Current THD	4%	4%	4%	4%
Passive Components	Smaller dc cap, Larger filter L	Smaller dc cap, Larger filter L	Larger dc cap, Smaller filter L	Larger dc cap, Smaller filter L
Voltage Stress on each Device	11 kV	11 kV	6 kV	6 kV
Current Stress in each Device	10A	10A	10A	10A
Efficiency (at 4 kHz)	99.54%	99.57%	99.43%	99.17%

Lower Voltage Stresses and DC Bus Voltage

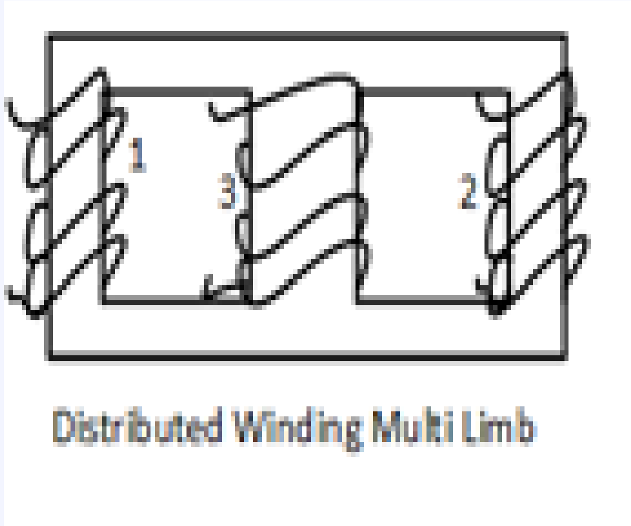
Higher Efficiency

A Number of Potential Inverter Topologies Have Been Explored for AC Grid Tie

Task 2 : DC-DC Integrated Converter Modules



Single Core, 3-Winding Distributed >30kW Prototype

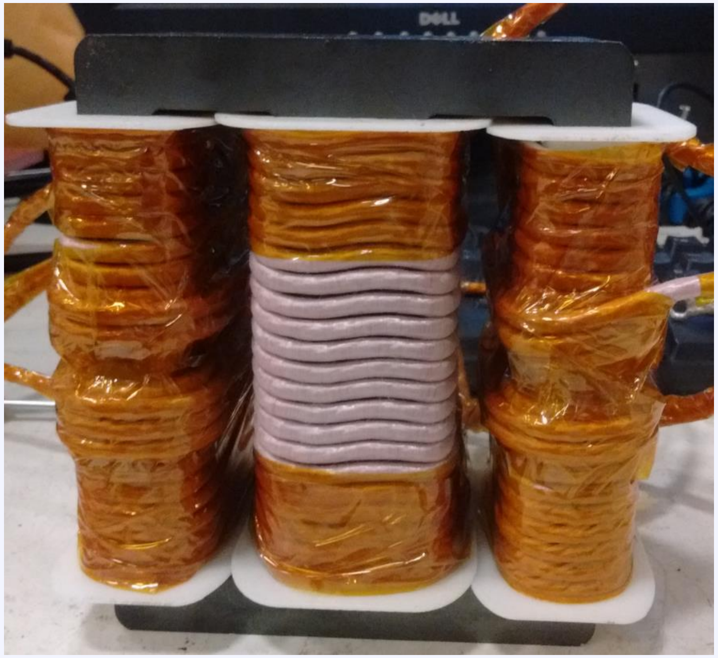


Three-Limb Core, 3-Winding <30kW Prototypes

Transformer Prototypes Being Explored:

- Prototypes < 30kW : Emphasize 3-Limb, 3-Winding
  - Reduced inter-winding capacitive coupling, additional design flexibility
- Prototypes > 30kW : Explore Single Core, 3-Winding
  - Begin simple for manufacturability, increase complexity as needed

Task 2 : DC-DC Integrated Converter Modules



Transformer Parameters		
Parameters	Measured Values	FEA Analysis
L_{L3}	89µH	82µH
L_{L1}	33µH	36µH
L_{L2}	38µH	36µH
C_{1a1b}	12pF	6pF
C_{1a2a}	5pF	6pF
C_{1a2b}	1pF	4pF
C_{1a3}	18pF	14pF
C_{2a1b}	7pF	4pF
C_{2a2b}	3pF	6pF
C_{2a3}	17pF	14pF
C_{1b2b}	12pF	6pF
C_{1b3}	14pF	14pF
C_{2b3}	16pF	14pF

FEA Compared with Experimentally Determined Results Using Equivalent Circuits Including Leakage Inductance and Parasitics to Confirm Effective Transformer Parameters

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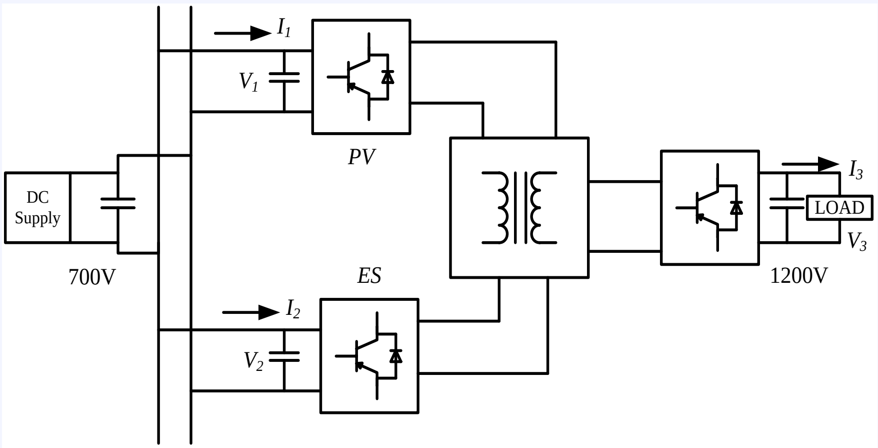
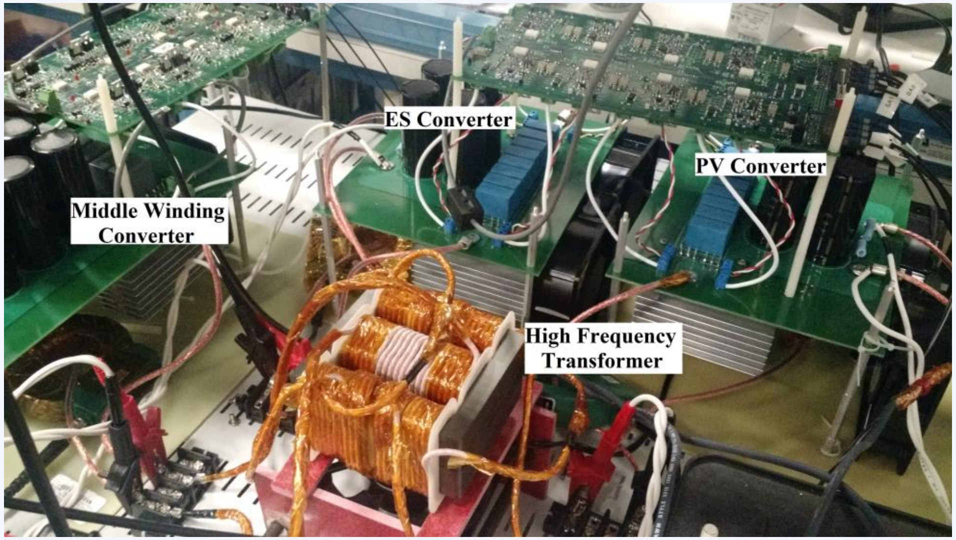
Task 2 : DC-DC Integrated Converter Modules





$$P_{PV} = V_1 I_1$$
$$P_{ES} = V_2 I_2$$
$$P_3 = V_3 I_3$$

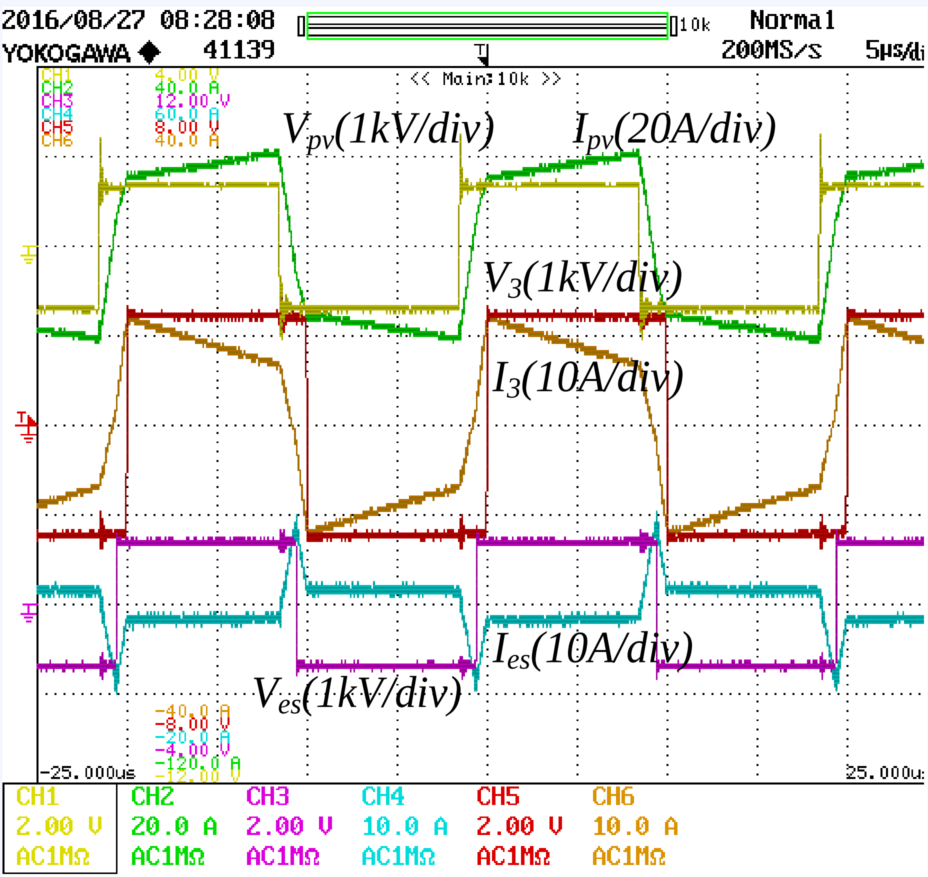
$$\text{when } P_{ES} > 0,\ P_{in} = P_{PV} + P_{ES}\ ,\quad P_{out} = P_3$$
$$\text{when } P_{ES} < 0,\ P_{in} = P_{PV}\ ,\quad P_{out} = P_3 + |P_2|$$

$$P_{losses} = P_{in} - P_{out}$$

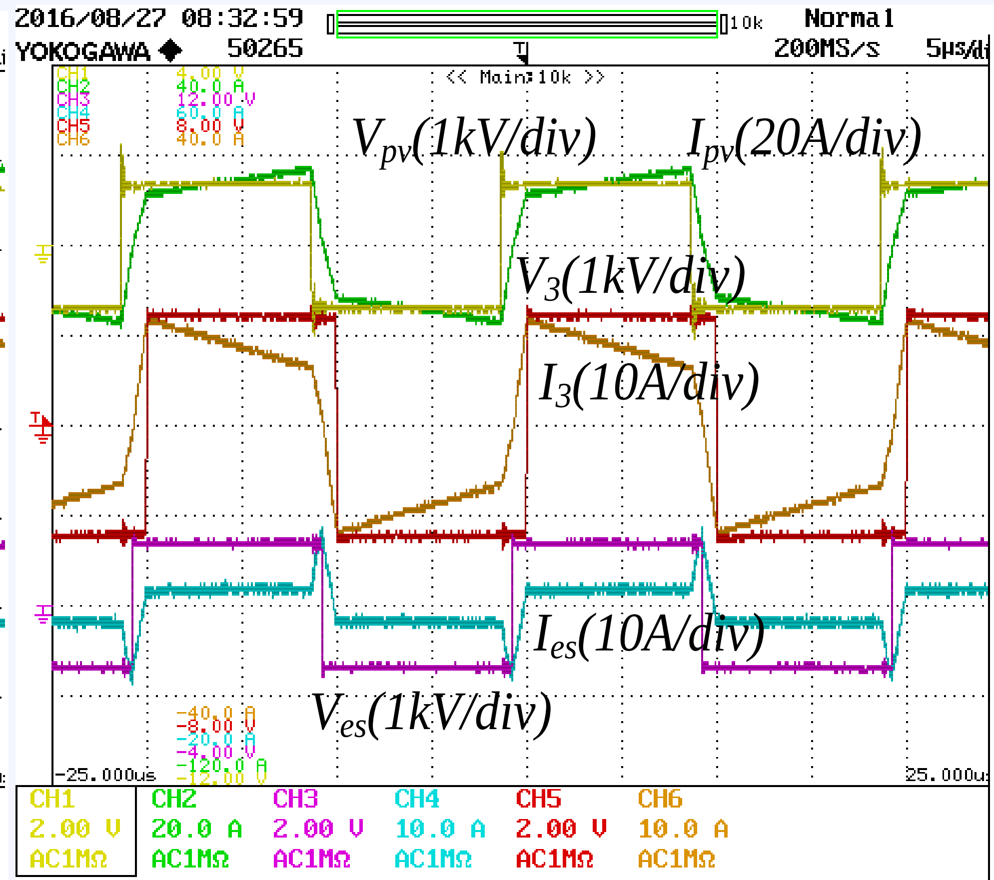
The First Full ~10kW Converter Prototypes Have Been Established for Commercially Available Ferrites and Nanocomposite Based Cores:

1) PV and ES Modeled as a DC Supply or Sink
2) A Single DC Bus 700V Input and 1200V DC Output Bus
3) Currently Open Loop Control, Control Issues To Be Explored

Task 2 : DC-DC Integrated Converter Modules



PV delivering 10.6 kW, ES taking 970W, 9.5kW load



PV delivering 6.4 kW, ES delivering 3.2kW, 9.5kW load

Successful DC-DC Converter Operation is Demonstrated for a Range of Various Use Case Scenarios

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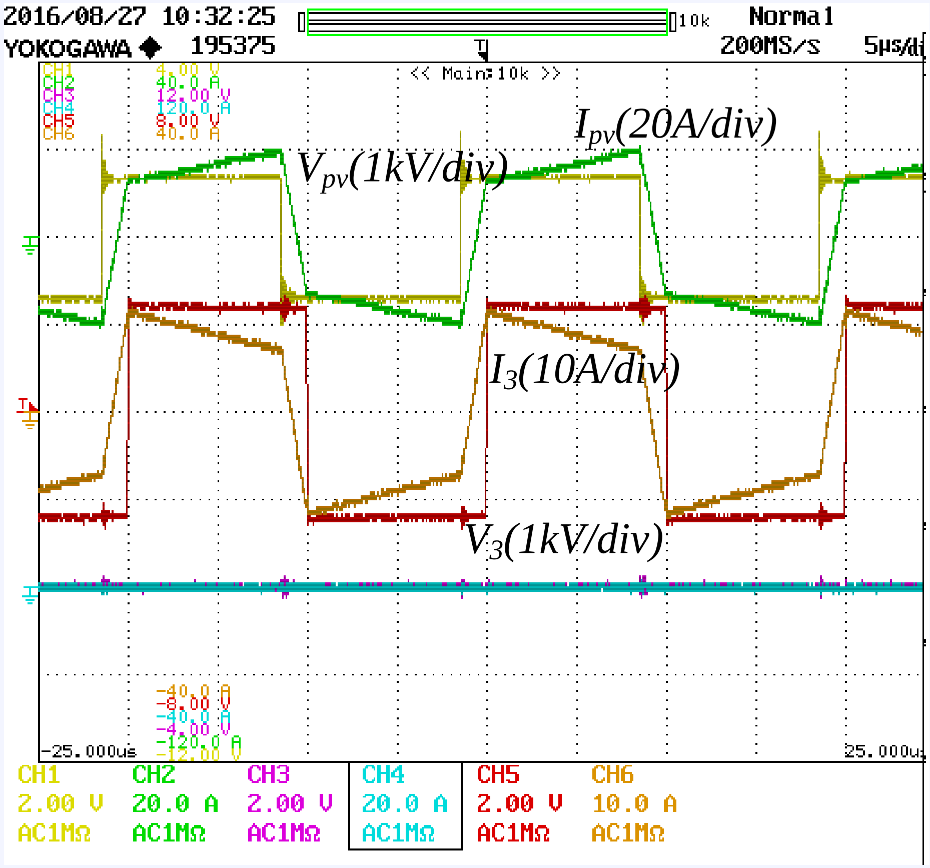
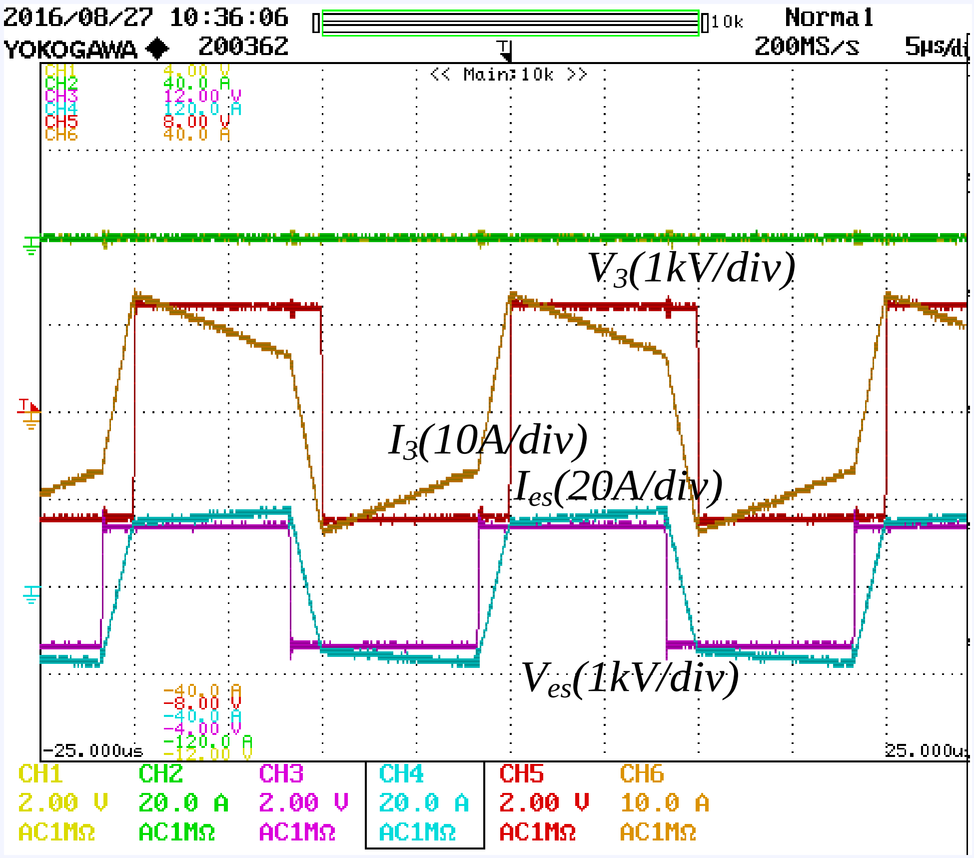
Task 2 : DC-DC Integrated Converter Modules



PV delivering 9.5kW, ES is idle



PV is idle, ES delivering 9.5kW

Successful DC-DC Converter Operation is Demonstrated for a Range of Various Use Case Scenarios

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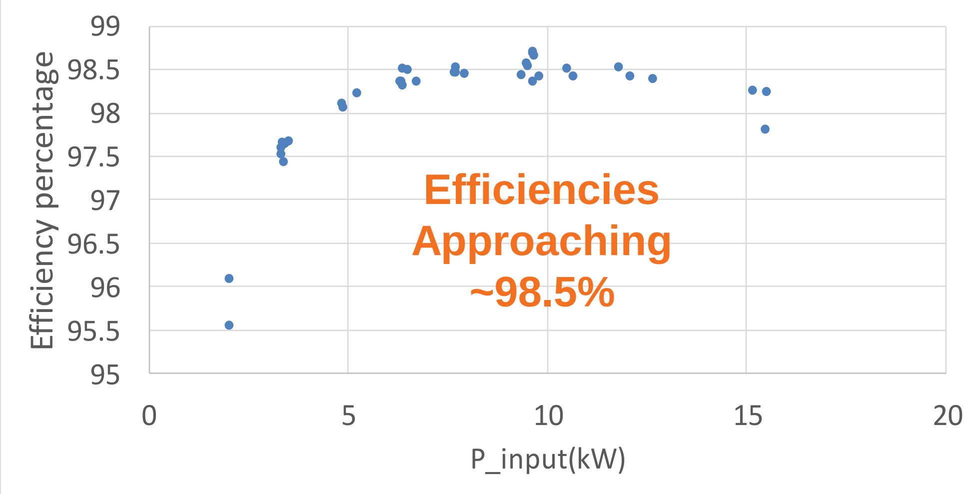
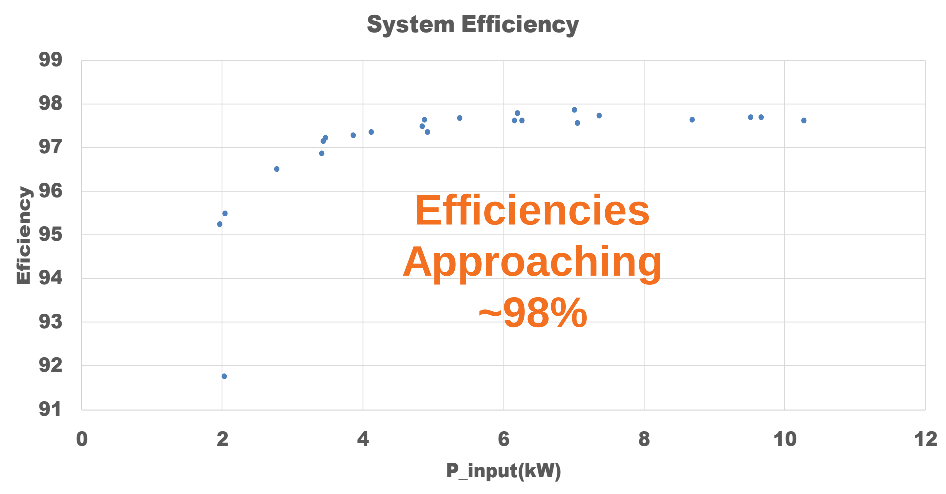
Task 2 : DC-DC Integrated Converter Modules

Early Stage ~10kW DC-DC Converter Prototype Results





MnZn-Ferrite Core Based Transformer

at 0.2T, 50kHz

Vitroperm 8000 Nanocomposite Core Based Transformer

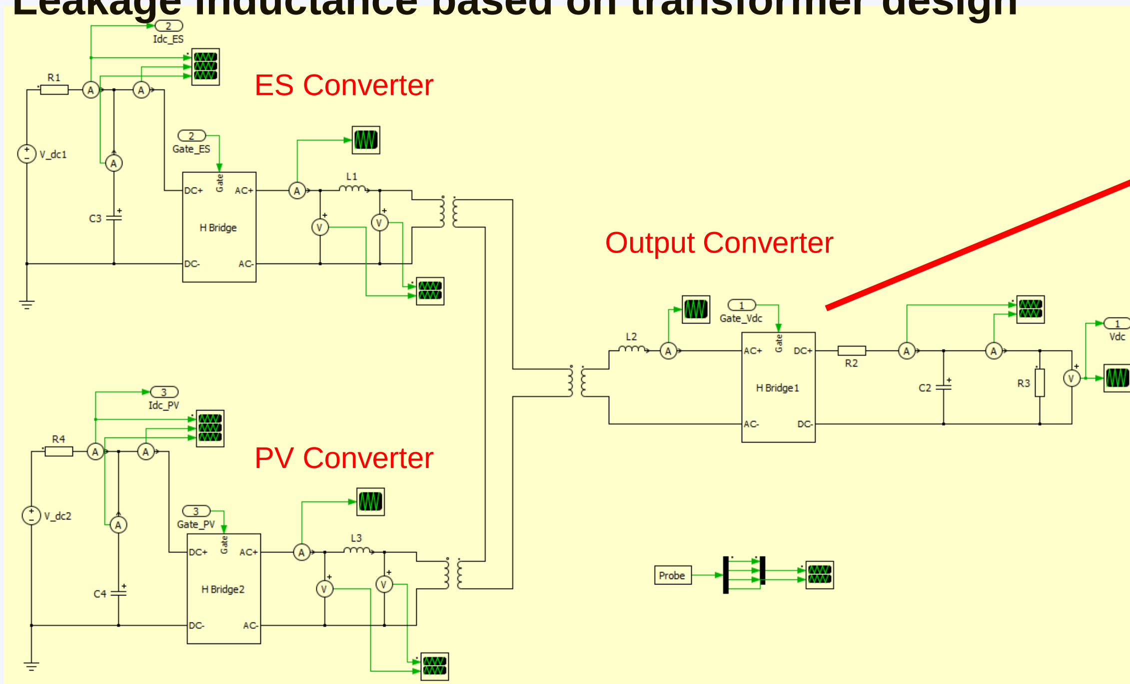
at 0.5T, 20kHz

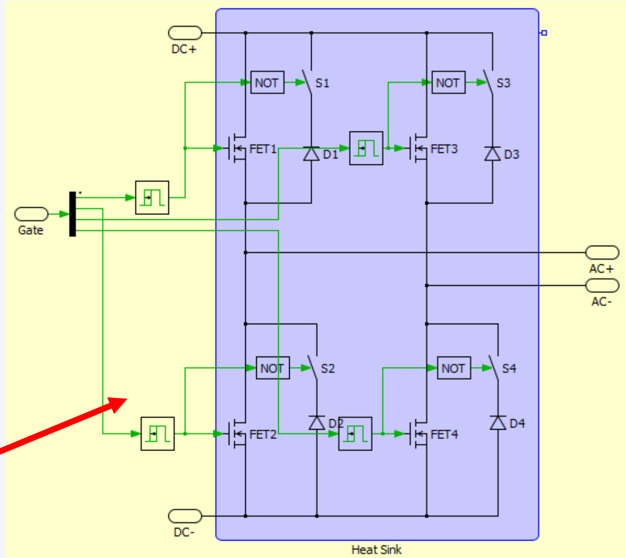
Higher Efficiencies are Achieved at Higher Inputs Powers.

Efficiencies Approaching 98-98.5% for Early Prototypes that Have Not Been Loss Optimized.

Task 2 : DC-DC Integrated Converter Modules

- Single core transformer model
- MOSFET based H-bridges for all limbs
- 1:1:1 transformer turns ratio
- Infinite magnetization inductance
- Leakage inductance based on transformer design





H-Bridge

Simulations Have Been Performed for the Full 50kW Prototype DC-DC Converter Module Using Idealized Transformer Models and Commercially Available SiC-Based Device Characteristics Taken from Data Sheets

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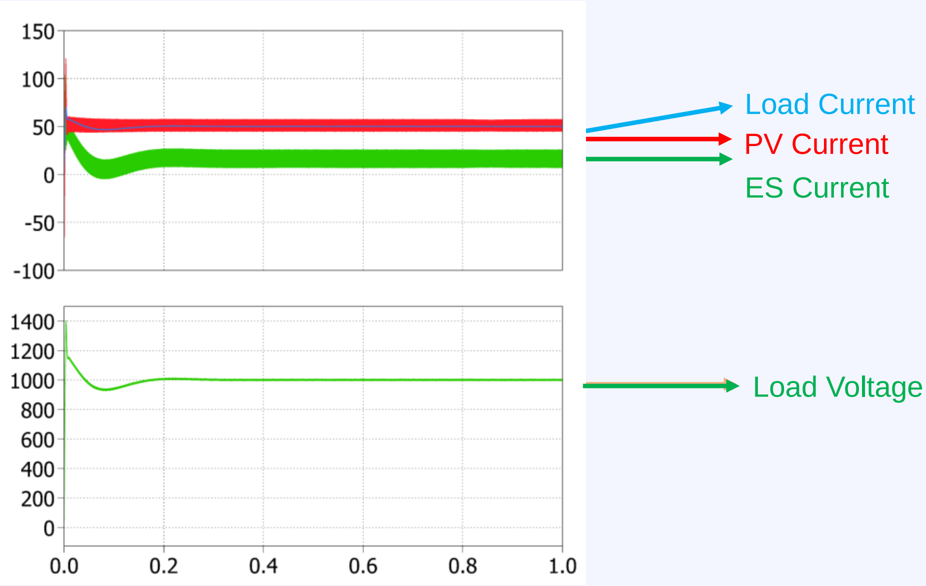
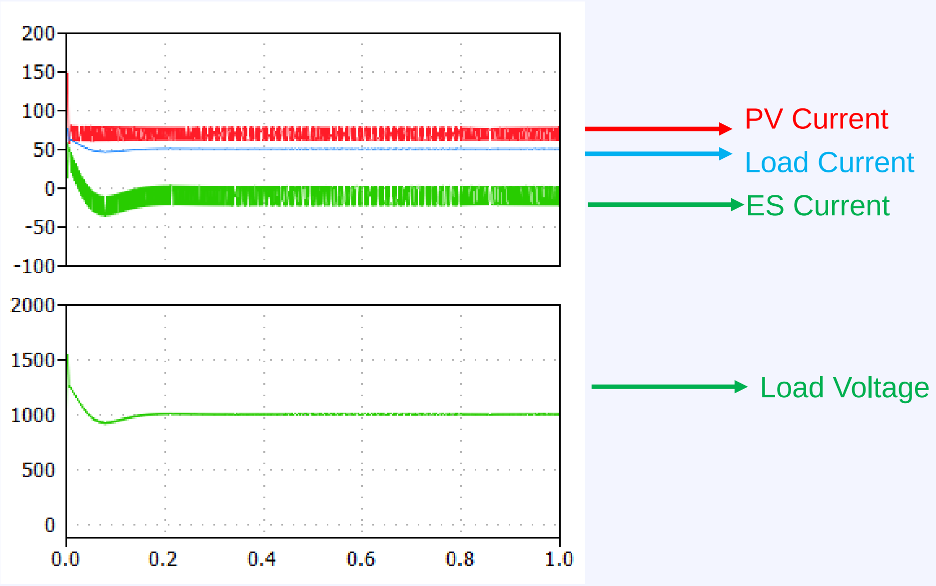
Task 2 : DC-DC Integrated Converter Modules

40kW PV Output
10kW ES Output
50kW DC Output



55kW PV Output
5kW ES Input
50kW DC Output

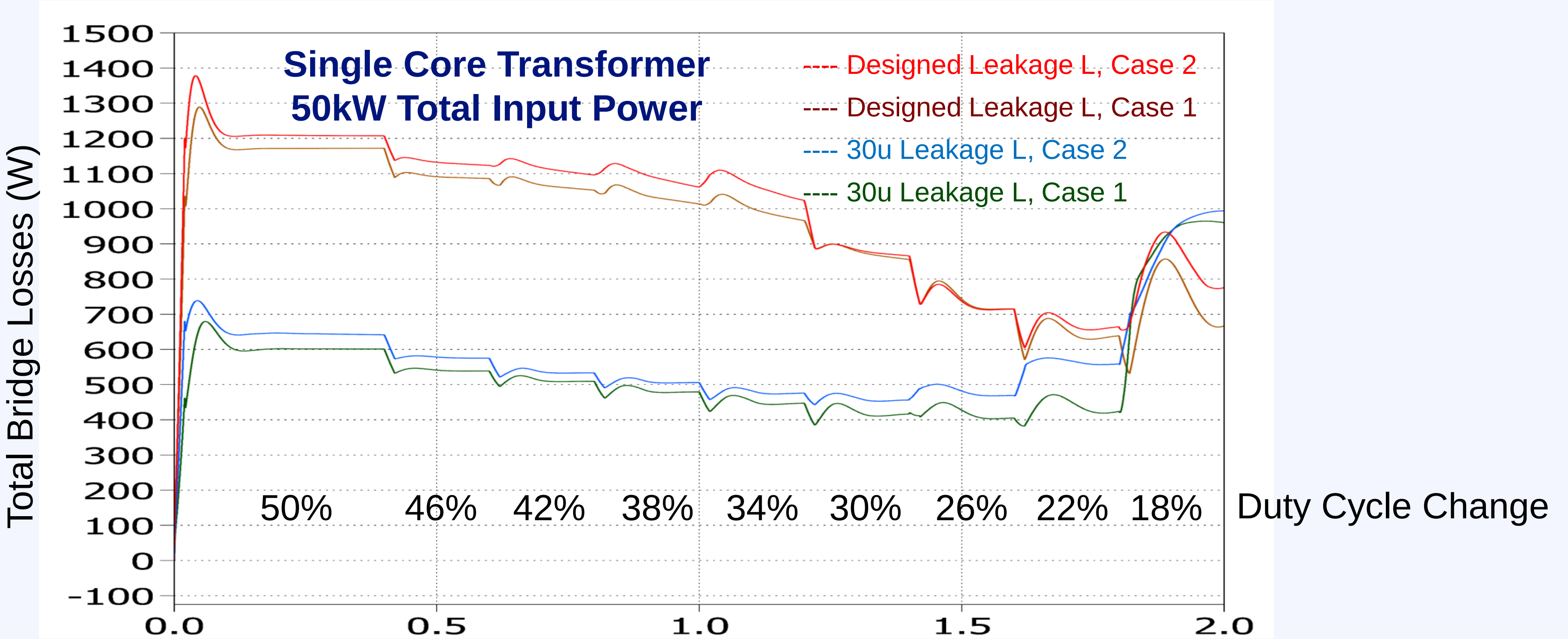


Example Simulation Results for Two Different Use Cases:

Use Case #1: PV and ES Distributing Power to Load

Use Case #2: PV Distributing Power to Both ES and Load

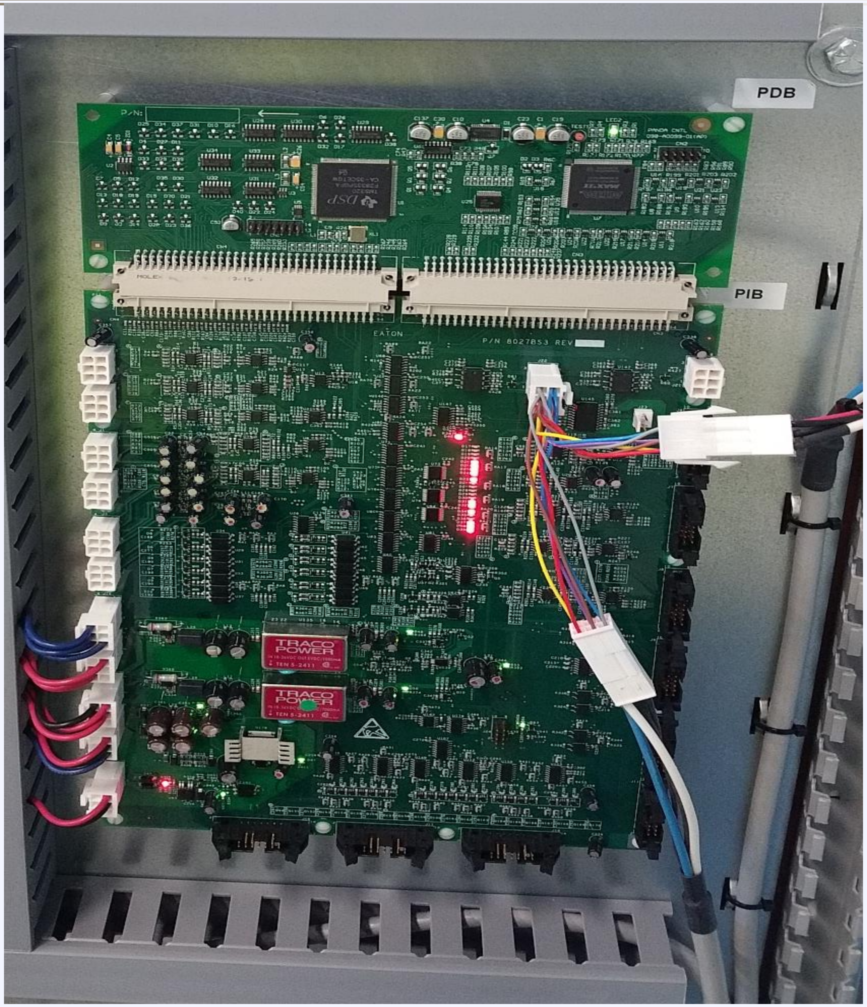
Task 2 : DC-DC Integrated Converter Modules



Duty Cycle Control and Leakage Inductance Modifications Enables Semiconductor Losses <1% Required to Achieve Converter Metrics.

Further Optimization with Controls and Semiconductor Design Will Be Pursued in Q3, Including More Realistic Transformer Models.

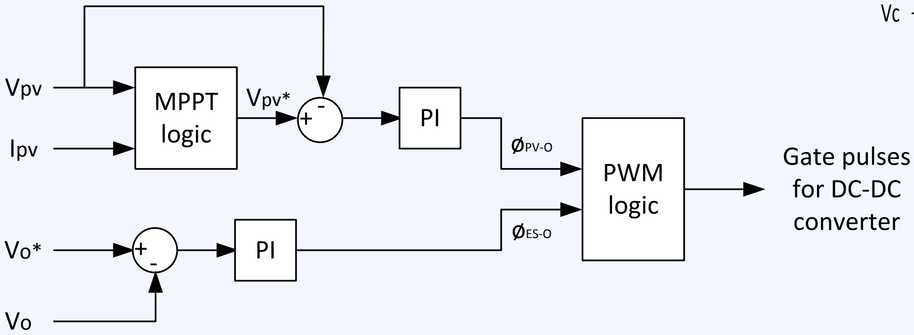
Task 2 : DC-DC Integrated Converter Modules



Suitable Controller Hardware Compatible with Existing Eaton Commercial Inverters Has Been Identified

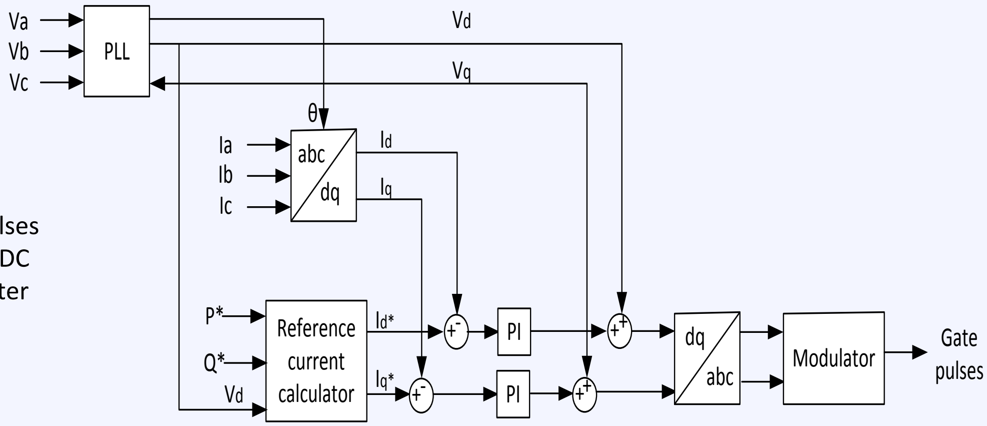
Task 3 : System Level Integration Simulation and Experimental Demonstration

- Three-port DC-DC converter control



- Perturb & observe MPPT algorithm
- Regulated output voltage
- Phase-shift control for three-port DAB

- Inverter Control



- Active and reactive power control using inverter
- Control in synchronously rotating frame
- Space vector modulation of inverter

Control Structures Were Developed and Implemented Including MPPT w/ Voltage Control of 3-Port Converter.

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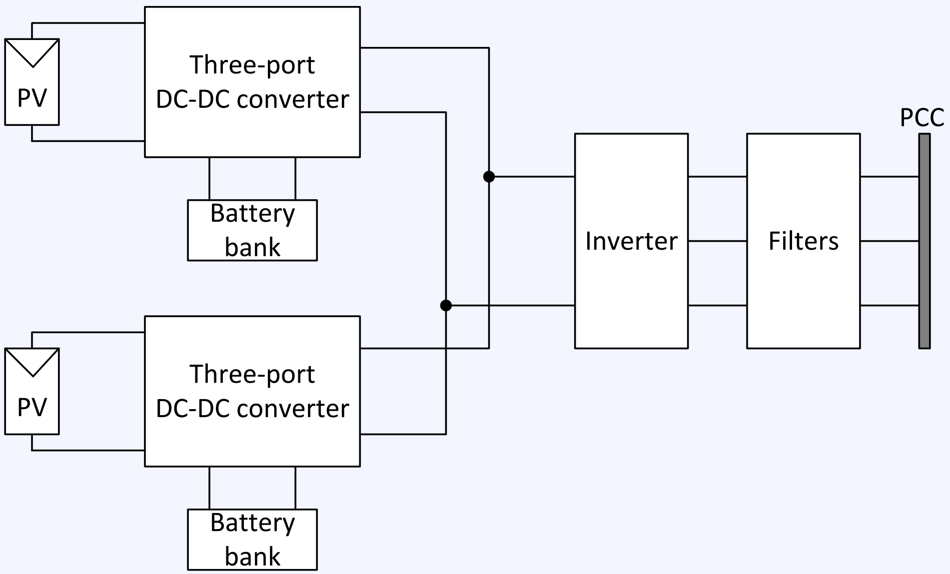
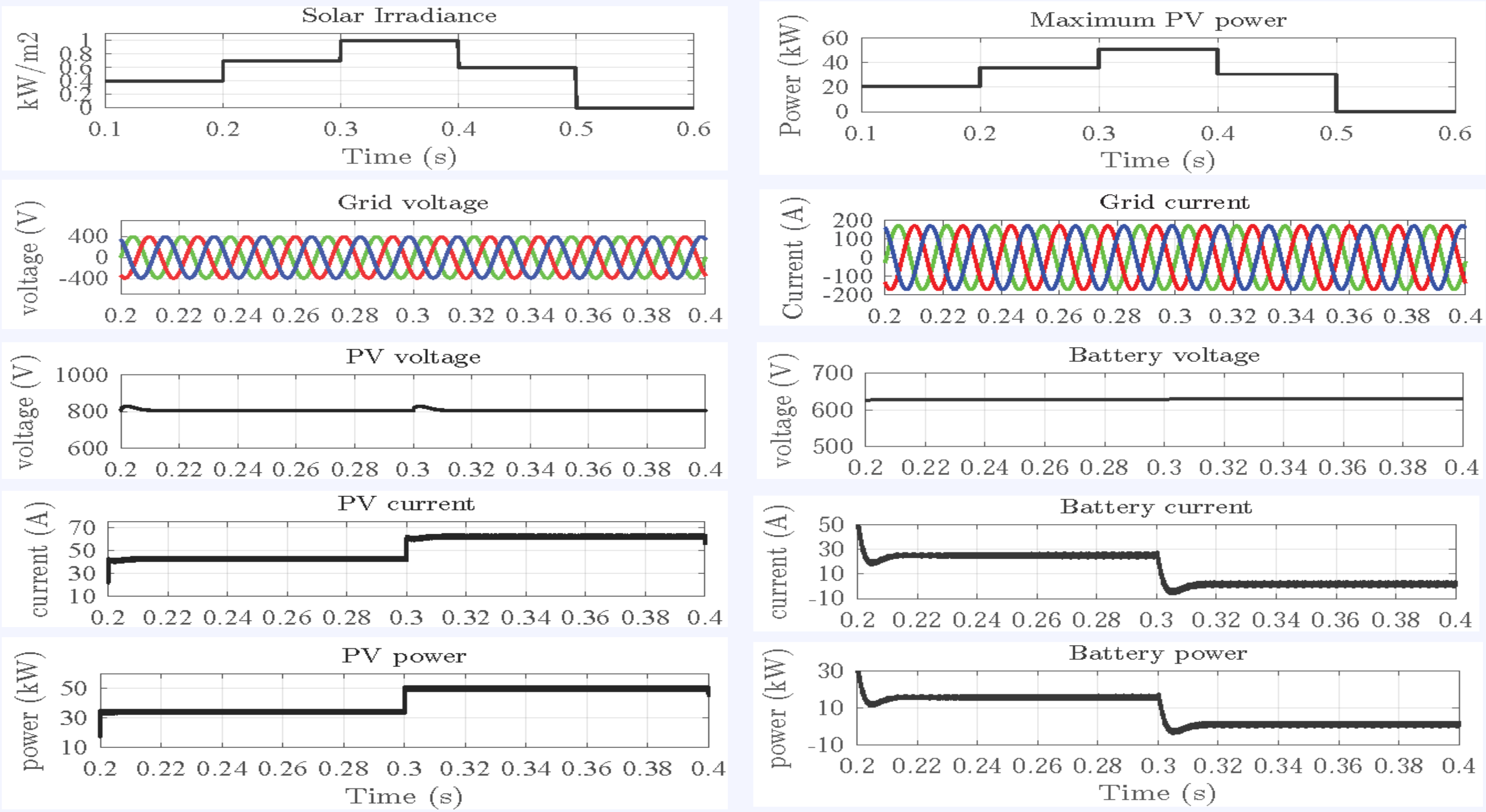
Task 3 : System Level Integration Simulation and Experimental Demonstration

- Rated power: 100 kW
- AC voltage: 480 V
- Rated frequency: 60 Hz
- 50 kW, DC-DC module
- 2 Parallel DC-DC modules
- PV voltage: 600-1000 V
- ES voltage: 480-672 V
- DC-DC o/p voltage: 800 V



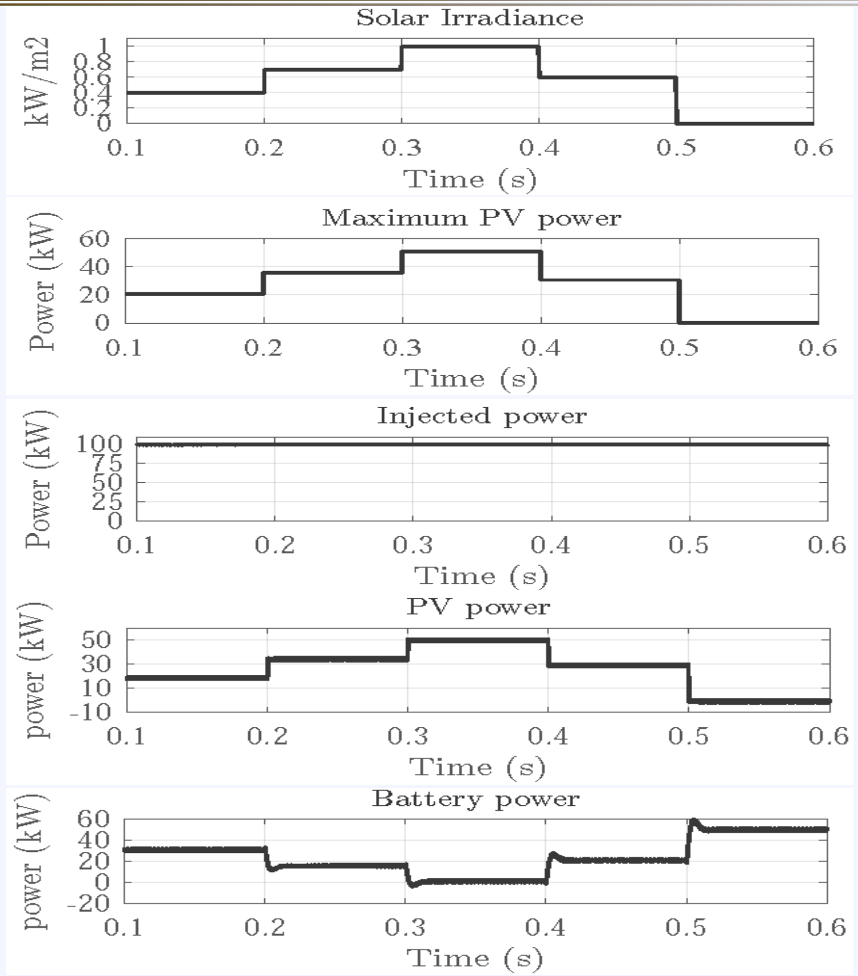
Integration of 2 – 50kW DC-DC Converter Modules Consistent with Planned Experimental Demonstration.

Task 3 : System Level Integration Simulation and Experimental Demonstration



Use Case Showing Converter Response to Increased Solar Irradiance with Fixed Inverter Output Power.

Task 3 : System Level Integration Simulation and Experimental Demonstration



Base Load Operation

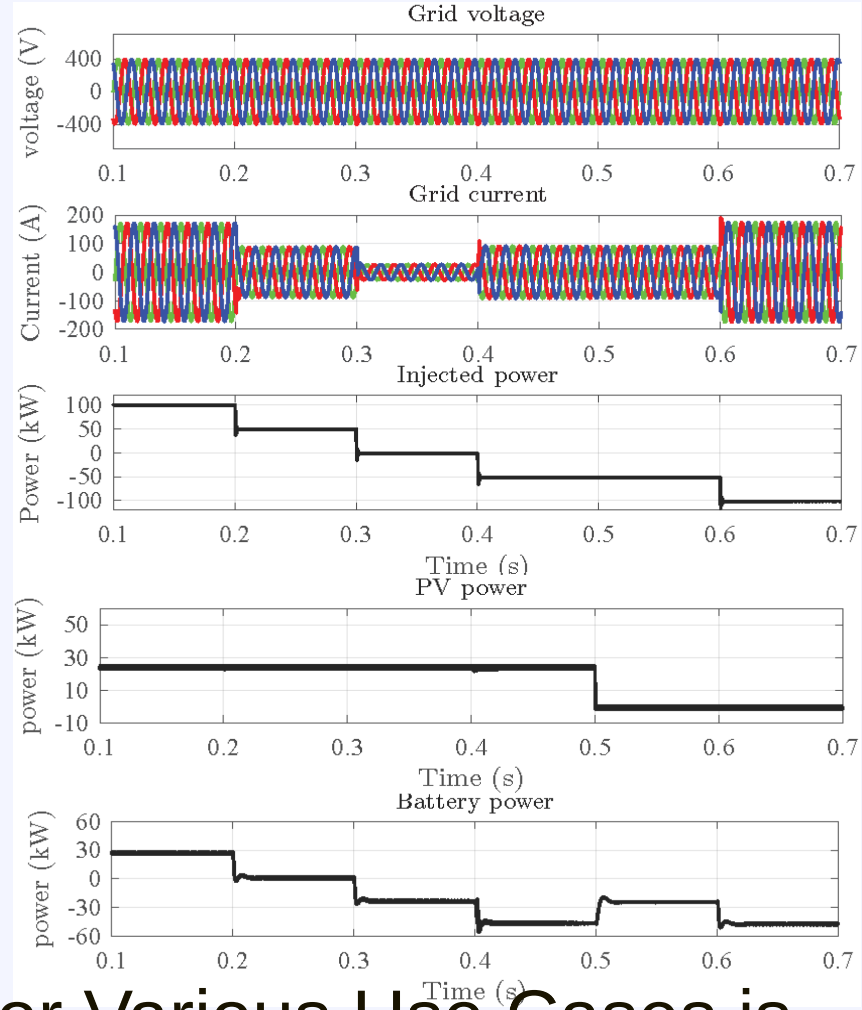
- System behaves as a base load plant
- MPPT algorithm efficiently tracks maximum power point
- Help mitigating issues associated with the increased PV penetration
- Battery absorbs PV fluctuations

Base Load Operation Under Varying Solar Irradiance Conditions is Demonstrated with Fixed Output Power.

Task 3 : System Level Integration Simulation and Experimental Demonstration

Dispatchable Operation

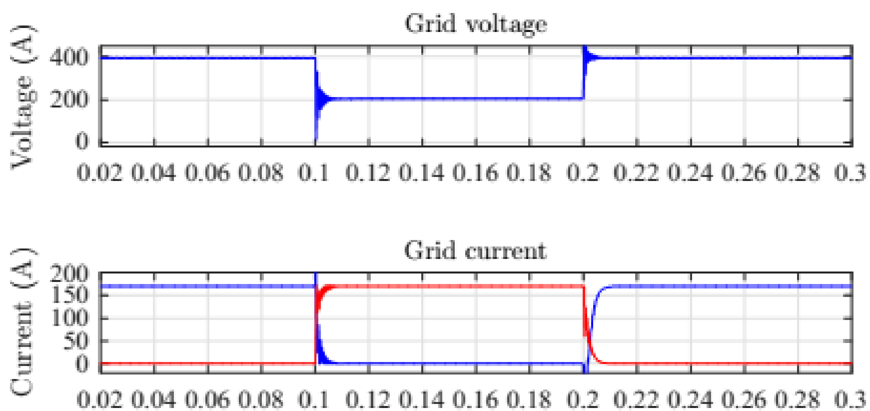
- System behaves as a dispatchable PV plant
- 0.3 s-0.4 s: Battery is charged from PV
- 0.4 s-0.5 s: Battery is charged in using both PV and grid
- 0.5 s–0.7 s: Battery is charged from the grid



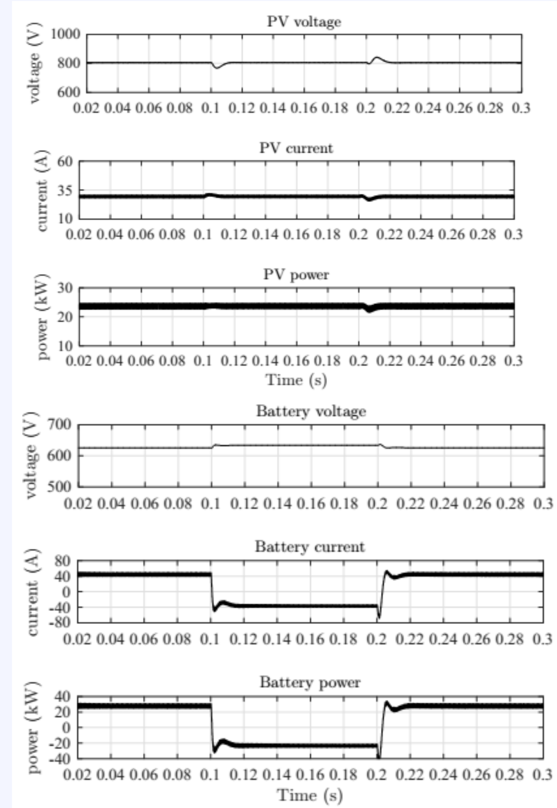
Dispatchable Operation for Various Use Cases is Demonstrated Including ES Charging / Discharging.

Task 3 : System Level Integration Simulation and Experimental Demonstration

Low Voltage Ride Through (LVRT)



- 50 % Voltage dip at t=0.1 s.
- Restoration at t=0.2s.
- LVRT requirements:
  - Active current injection should be reduced to zero on voltage dip.
  - Full reactive current injection during voltage dip.
  - Restore active current injection on fault clearance.
- Solar irradiance: 0.5 kW/m^2

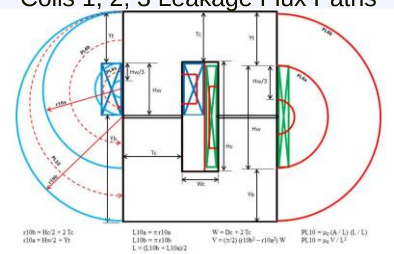


LVRT Can Be Accomplished in the Current Topology Through ES Charging Rather than Shifting From MPPT.

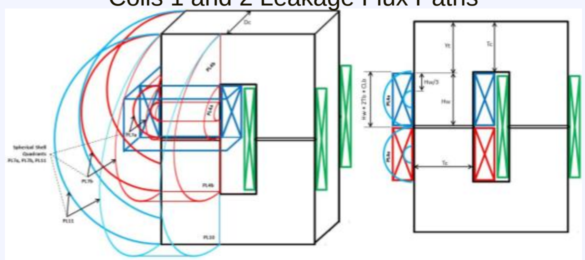
Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

Permeance Based Leakage Inductance

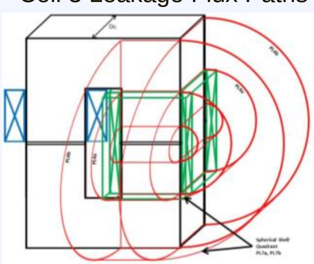
Coils 1, 2, 3 Leakage Flux Paths



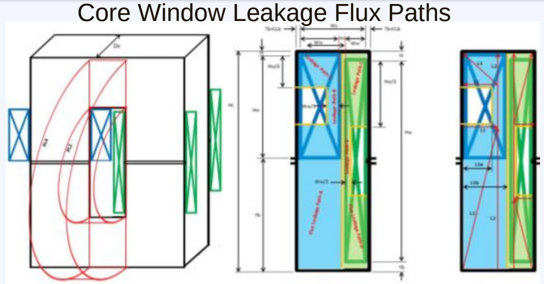
Coils 1 and 2 Leakage Flux Paths



Coil 3 Leakage Flux Paths

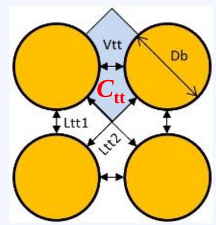


Core Window Leakage Flux Paths



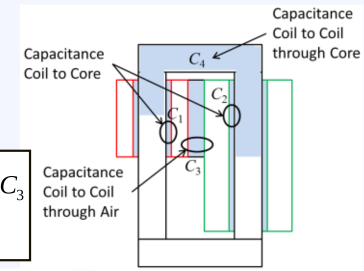
Analogous Interwinding Capacitance Models

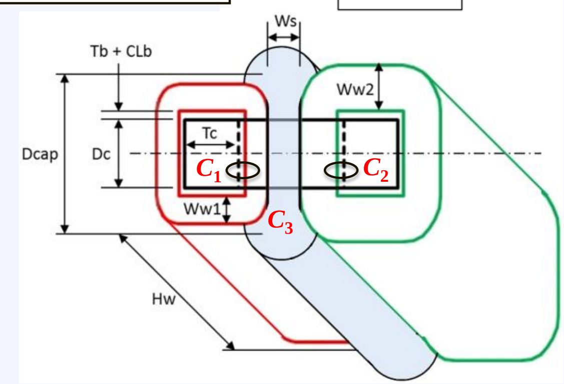
C_{tt}
Intra-Coil Turn to Turn Capacitance



C_{cc}
Inter-Coil Coil to Coil Capacitance

$$C_{cc} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_4}} + C_3$$





Existing Analytical Models for Leakage Inductance and Parasitic Capacitances Have Been Developed and Applied for Integration with Transformer Designs.

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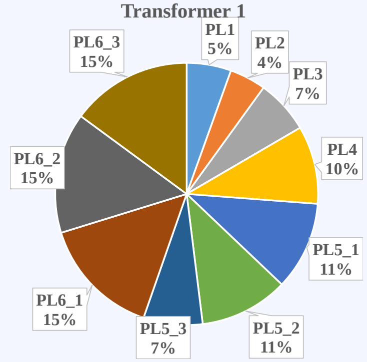
Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

~70% of Permeance Dictated By Winding Geometry



Relative Permeances for Transformer 1

TABLE 1: Transformer Physical Data		
	Design 1	Design 2
	V/N= unequal	V/N = equal
PV voltage rating	700V	700V
ES voltage rating	700V	700V
Middle Limb voltage rating	1200V	1200V
Cores used	E-100/60/28	I-93/27/16
Side Limb Area	13.5mmx54mm	16mmx54mm
Middle Limb Area	27mmx54mm	16mmx54mm
Side limb no of turns	24	20
Middle limb no of turns	20	34
Clearance+Bobbin thickness CL_s and CL_m	2.5 mm each	2.5 mm each

TABLE 2: Transformer Parameter Comparison				
		Analytical	FEA	Measured
Leakage from Middle Winding	TR1	131µH	129µH	134µH
	TR2	403µH	402µH	386µH
Leakage from PV Winding	TR1	189µH	188µH	174µH
	TR2	132µH	131µH	143µH
Leakage from ES Winding	TR1	189µH	188µH	176µH
	TR2	132µH	131µH	135µH
Capacitance between PV-HV	TR1	29pF	32pF	32pF
	TR2	27pF	26pF	24pF
Capacitance between ES-HV	TR1	29pF	32pF	31pF
	TR2	27pF	26pF	23pF
Capacitance between ES-PV	TR1	22pF	25pF	22pF
	TR2	23pF	22pF	20pF

Consistency Has Been Achieved Between Analytical Calculations, Finite Element Analysis, and Measured Values of Prototypes.

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Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

Transformer Performance and Design 2016-Sep-03 M. A. Juds

Power			Input	
Desired Ouput Power	P-out	watts	50,000	
Frequency	f	Hz	10,000	
Primary Voltage	Vp	v-rms	600	849 v-pk

Windings			Input		
Solid wire ---or--- Litz wire		S -or- L	l	Litz	
			Coil-1	Coil-2	Coil-3
Turns	N	Turns	8	8	8
Wire Size	awg	awg	2	2	2
Litz Equivalent Wire Size		awg	2	2	2
Number of Insulated Strands		---	1320	1320	1320
Strand Size		awg	33	33	33
Diameter over Insulation		inch	0.484	0.484	0.484
DC - Winding Resistance	Rdc	ohm-DC	1.90E-03	1.90E-03	1.69E-03
AC - Winding Resistance	Rac	ohm-AC	1.99E-03	1.99E-03	1.77E-03
Coil Mass	M	kg	1.10E+00	1.10E+00	9.79E-01
Load Resistance	R	ohms	R2, R3	4.400	4.400
Suggested Resistance ... (R = Vs^2 / P-out)			(Coil 1-2), (Coil 1-3)	6.489	4.400
			(Coil 3-2), (Coil 2-3)	4.400	4.400

Bobbin			Input		
Bobbin Thickness	Tb	inch	0.050		
Bobbin Clearance	CLb	inch	0.010		
Space Between Coils - Minimum	Ws	inch	0.100		
Winding Height	Hw	inch	2.560	2.560	5.120
		Hw Max.	< 4.081	< 4.081	< 4.081
		Hw Min.	0.510 <	0.510 <	0.510 <
No. of Winding Layers	N-Lay	Layers	2	2	1

Core Size			Input	Suggested Tc , Wc (inch)
Air Gap across Split in Core	g	inch	0.002	
Core Thickness	Tc	inch	3.400	Coil 1-2 = 2.48
Core Depth	Dc	inch	3.400	Coil 1-3 = 2.48
Core Stacking Factor	Sf	ratio	0.85	Coil 2-3 = 2.48
Core Flux Area	Tc Dc Sf	inch^2	9.826	Coil 3-2 = 2.48
Core Inside Width	Wc	inch	1.751	
Core Inside Height	Hc	inch	5.350	
Core Mass	Mc	kg	34.02	

Core Material Properties			Input	
Core Material ...	ARPA-E core-1 - VIM-39 Double Impreg			
Enter CUSTOM Properties ---or--- use ACCEPTED Values ...			Accepted Values	
			Custom	Accepted
Material Rel. Permeability	ur	---	150,000	41,422
Max. Linear Flux Density	Bmax	T	0.5	0.5
Core Density	d	kg/m^3	7,600	7,600
Core Resistivity	r	ohm-m	1.10E-06	1.10E-06
Core Dielectric Constant	er	---	0.00E+00	0.00E+00
Steinmetz Core Loss Coefficients	K	---	8.37E-07	9.66E-06
Pc = K f(Hz)^a B(T)^b w/kg	a	---	1.83	1.6516
	b	---	2.05	1.9616
Core Loss (at f & Bmax)	Pc	w/kg	10.02	
Max. Lam. Thickness	2x Skin	inch	0.00102	
Core Loss Solution - **Iterate** or **Estimate**		I / E	i	Iterate

Note: If ERRORs occur, Toggle to "E" and back to "I" to RESET the calculations.

P = Primary, S = Secondary			Results: Coils 1-2	Coils 1-3	Coils 2-3	Coils 3-2
Core Magnetic Flux			P=1, S=2	P=1, S=3	P=2, S=3	P=3, S=2
Prim. Core Flux Den.	Bp	Tesla-pk	0.27	0.27	0.27	0.27
Sec. Core Flux Den.	Bs	Tesla-pk	0.25	0.21	0.21	0.21
Core Rel. Permeability	ur-core	---	5,996	---	---	---
Flux Phase Angle P to S	Angle	degrees	17.5	38.0	38.0	38.0
Flux Leakage	Leak	%	4.9%	21.7%	21.7%	21.7%
Coil Performance			Coils 1-2	Coils 1-3	Coils 2-3	Coils 3-2
Primary Current	ip	amp-pk	183.6	151.7	151.7	151.7
Secondary Current	is	amp-pk	183.1	150.8	150.8	150.8
Secondary Voltage	vs	volt-pk	805.6	663.3	663.3	663.3
Primary Coil Resist.	Rp	ohm	1.99E-03	1.99E-03	1.99E-03	1.77E-03
Prim. Core Loss Resist.	Rp-core	ohm	5.88E-03	8.62E-03	8.62E-03	8.60E-03
Secondary Coil Resist.	Rs	ohm	1.99E-03	1.77E-03	1.77E-03	1.99E-03
Secondary Load Resist.	Rs-L	ohm	4.400	4.400	4.400	4.400
Ouput Power	P-out	watts	73,741	50,002	50,002	50,002
Power Density	P-out / V	w/in^3	107.0	72.5	72.5	72.6
Efficiency	Eff	%	99.8%	99.7%	99.7%	99.7%
Losses & Temperature Rise			Coils 1-2	Coils 1-3	Coils 2-3	Coils 3-2
Heat in Primary Coil	Pcoil-p	watts	33.5	22.9	22.9	20.3
Heat in Secondary Coil	Pcoil-s	watts	33.4	20.1	20.1	22.6
Heat in Core	P-core	watts	99.0	99.2	99.2	99.0
Core Loss of Core	Pc-core	w/kg	2.9	2.9	2.9	2.9
Temp. Rise - Prim. Coil	ΔT-coil-p	°C	55	38	38	35
Temp. Rise - Sec. Coil	ΔT-coil-s	°C	55	34	34	37
Temp. Rise - Core	ΔT-core	°C	66	66	66	66

Inductance - Self & Mutual (h)

Coil I.D.	1	2	3
1	4.34E-03	4.33E-03	4.33E-03
2	4.33E-03	4.34E-03	4.33E-03
3	4.33E-03	4.33E-03	4.34E-03

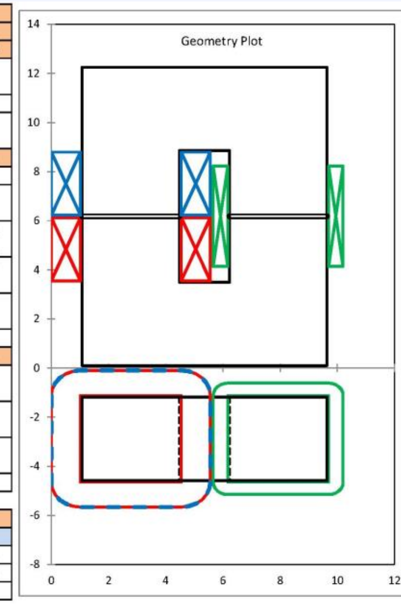
Inductance - Leakage (h)

Coil I.D.	1	2	3
1	---	2.21E-05	5.47E-05
2	2.21E-05	---	5.47E-05
3	5.47E-05	5.47E-05	---

Capacitance (f)

Coil I.D.	1	2	3
1	5.95E-11	1.07E-10	1.03E-10
2	1.07E-10	5.95E-11	1.03E-10
3	1.03E-10	1.03E-10	4.11E-11

Overall Size and Weight			Results
Height	H	in	12.15
Width	W	in	10.20
Depth	D	in	5.56
Volume (Core + Coils)	V	in^3	689.2
Mass (Core + Coils)	M	kg	37.2



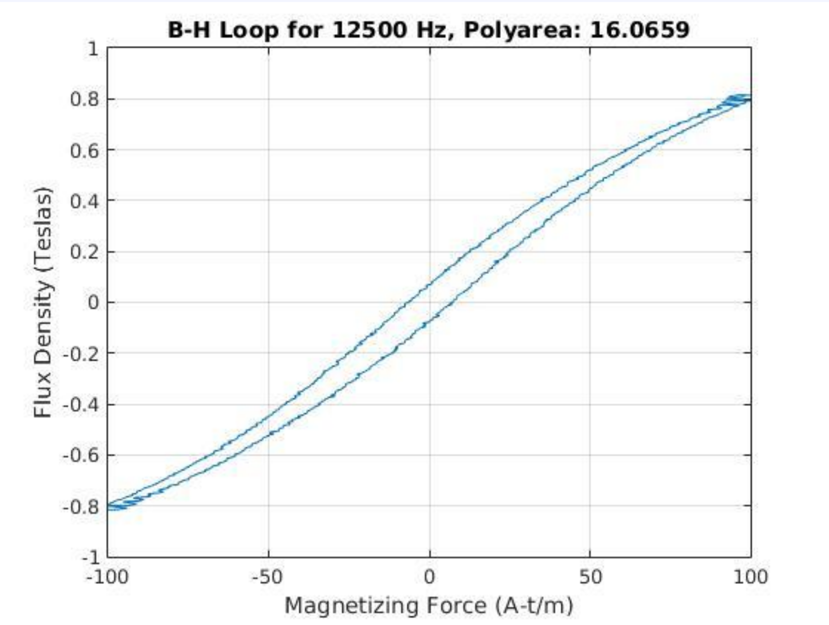
Design-Performance Summary

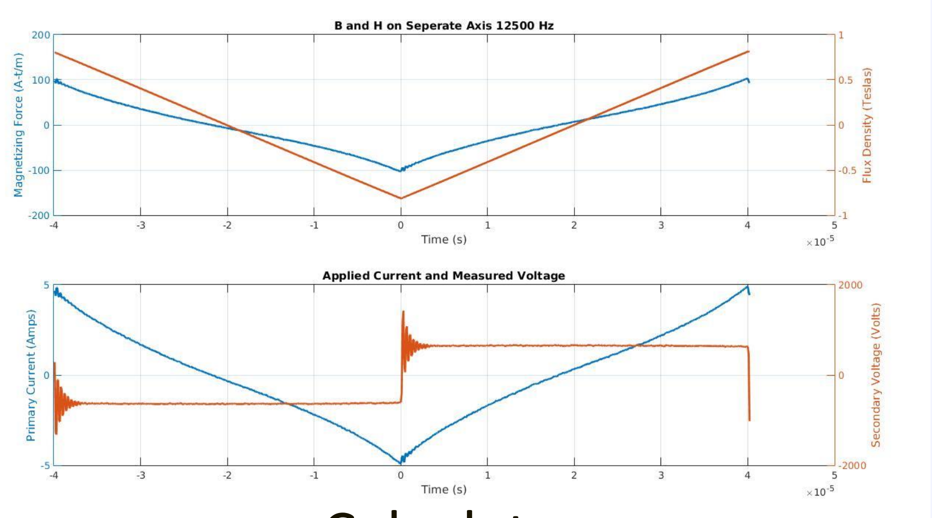
- 50 kW, 10 kHz
- Efficiency = 99.7%
- Power Density = 72.5 w / in^3
- Coils = 8 turns of 2 awg Litz Wire
- ARPA_E core-1 VIM-39

- Voltage: V_{Pri} = 849 v-pk V_{Sec} = 663.3 v-pk
- Current: I_{Pri} = 151.7 a-pk I_{Sec} = 150.8 a-pk
- Heat Dissipation: Q_{Pri} = 22.9 w Q_{Sec} = 20.1 w Q_{Core} = 99.2 w
- Temperature Rise: ΔT_{Pri} = 38° C ΔT_{Sec} = 34° C ΔT_{Core} = 66° C

Full-Scale Transformer Design Models are Under Development and Early Results Show Losses and Temperature Rises within Requirements for Transformer Performance.

Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing





- Calculates
  - Zero Crossing
  - Induction
  - Magnetizing Force
  - Power
  - Reactive Power

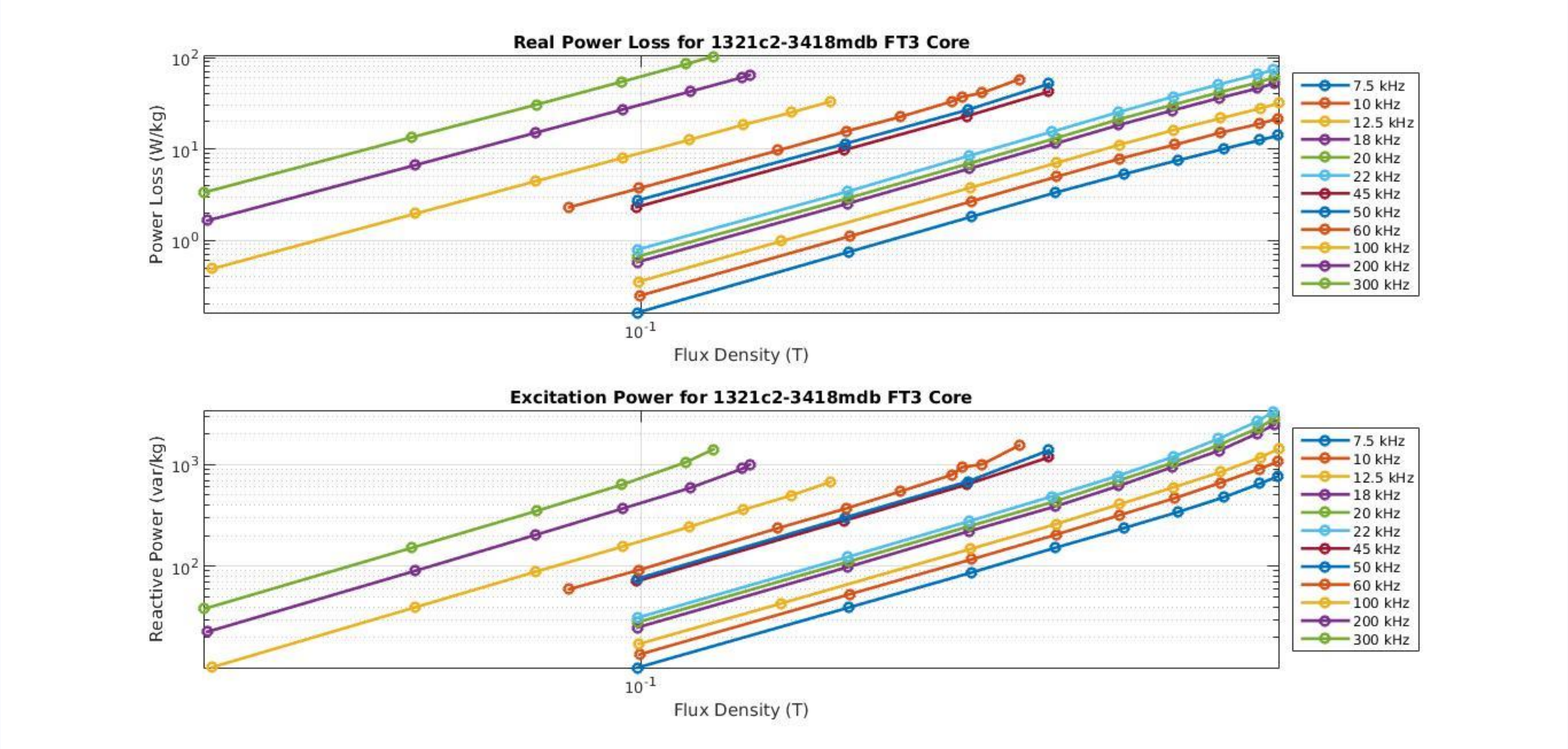
- Reads CSV
  - Primary Current
  - Secondary Voltage

$$H(t) = \frac{N_p\, i(t)}{l_e}$$

$$B(t) = \frac{1}{N_s A_e} \int_0^T v(t)dt$$

- A Custom Core Testing System was Established
- Square Wave, Varying Duty Cycle Excitation (1.5kV, 30A, 15kW)

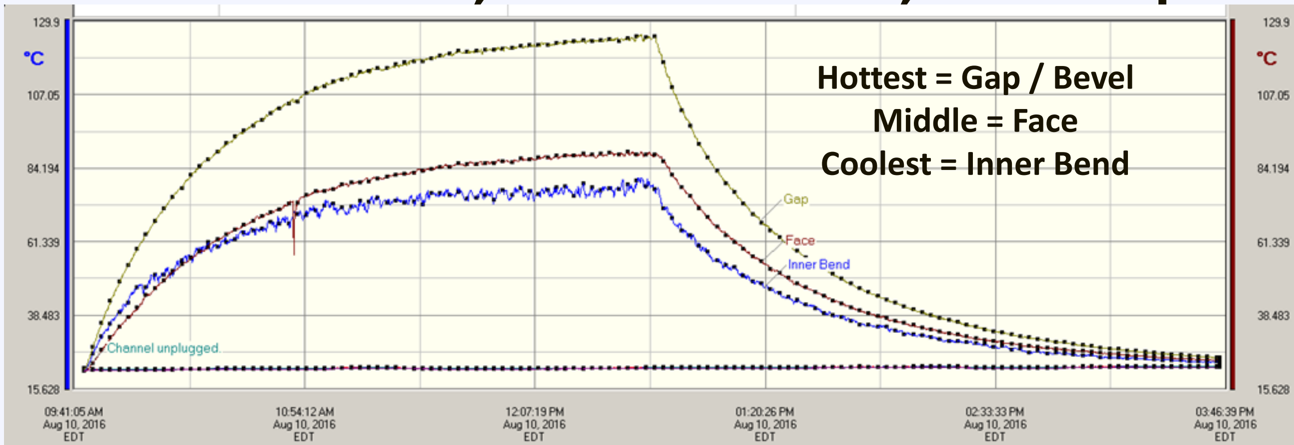
Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

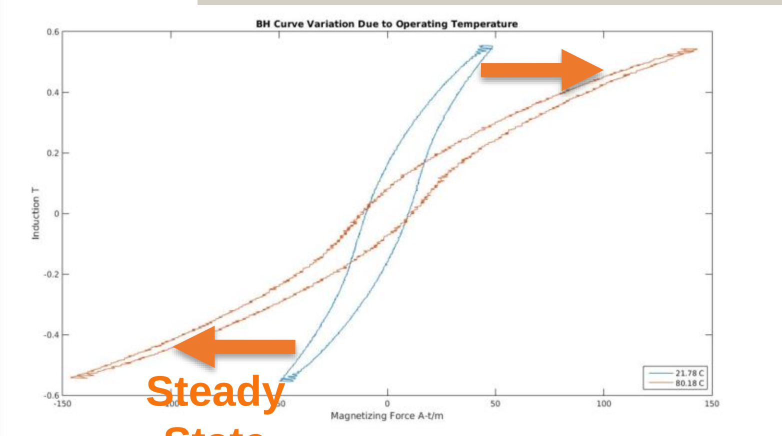


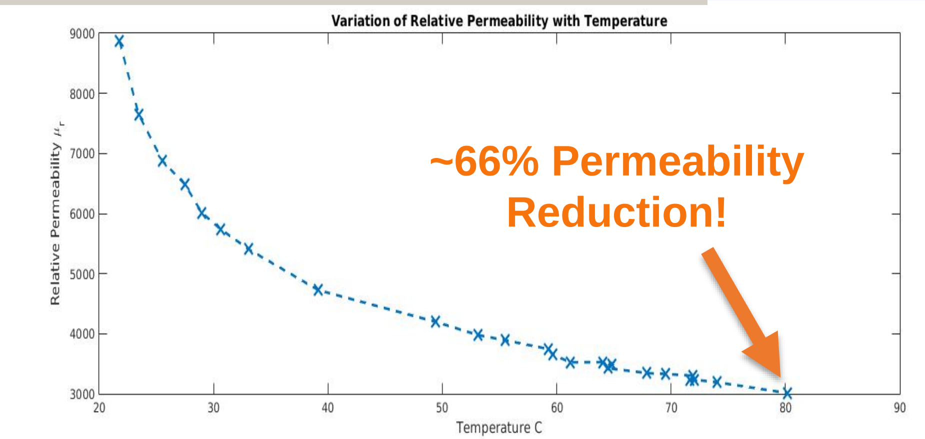
Measured Losses and Reactive Power are Accessible Under a Broad Range of Frequencies and Induction Levels (Commercial Fe-Based Nanocomposite Core).

Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

Finemet FT3 Core, 0.6 T Induction, 10kHz Square







Moderately High External Core Temperatures Result in Large Reductions in Effective Permeability (~66% Decrease!).

High Temperature Core Property Stability is Critical Even for Ambient Power Conversion.

Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

Four Primary Base Alloys Serve as the Project Start

Scale-Up Efforts Initiated in Q2, Several Pilot Casts

Base Alloy Classes	Alloy Archetype	Core Losses at 10kHz	Permeability Range	Temperature Stability	Mechanical Properties	TRL	Primary Alloy Development Objectives	Relevance to SunShot Initiative Targets
FeNbSiBCu	Fe-Based	Excellent	10^5 to 10^3	Up to ~150C	Needs Improvement	3-5	Magnetostriction Reduction, Mechanical Properties	Improved Core Level Manufacturability and Loss Performance
FeCoNbSiBCu	FeCo-Based	Good	10^4 to 10^2	Up to ~350C	Needs Improvement	3-5	Magnetostriction and Loss Reduction, Mechanical Properties	Improved Core Level Manufacturability and Loss Performance
CoNbSiBCu	Co-Based	Very Good	10^5 to 10^1	Up to ~500C	Satisfactory	2-4	Cost Reduction and Permeability Tuning	Reduced Costs, Parasitics, and Losses
NiFeNbSiBCu	NiFe-Based	TBD	TBD	TBD	TBD	2-3	Loss Reduction, Mechanical Properties, and Permeability Tuning	Reduced Costs, Parasitics, and Losses

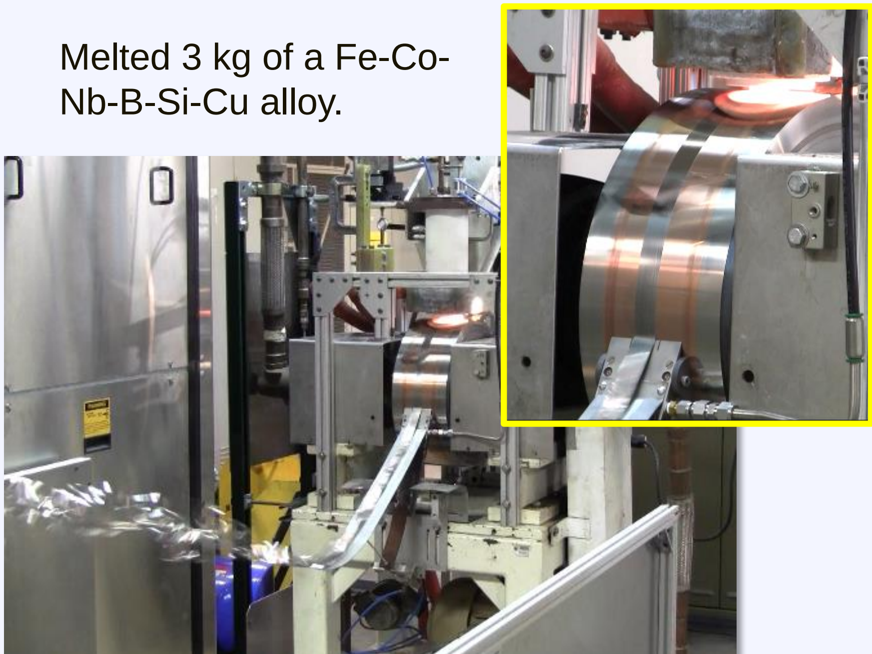
Modify Composition, Treatment for Optimized Losses ← **Laboratory Scale Alloy Development in Q2, Scale-Up to Be Pursued in Q3**

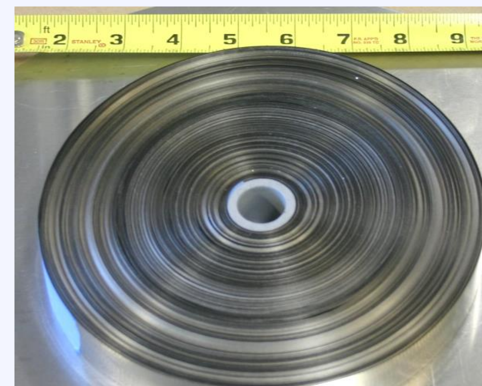
New Alloy Development at Laboratory Scale and Full Prototype Scale is also Underway to Improve Performance for Solar Inverter and Other Power Electronics Applications.

Task 4 : Advanced Magnetic Core and High Frequency Transformer Fabrication, Design, and Testing

Images from Run #03.

Melted 3 kg of a Fe-Co-Nb-B-Si-Cu alloy.





0.75 miles of coiled ribbon

- Pilot-Scale Caster Returned to Full Operational Status
- Several Successful Casts Were Performed
- Additional System Upgrades Implemented

Patents and Publications

- Presentations
  - Presentations at ECCE 2016, IECON 2016, and IAS Conference 2016
  - Three Abstracts Submitted to Magnetism and Magnetic Materials 2016
  - TMS Annual 2017 Conference Symposium Being Organized
  - 3 Invited Presentations at MRS Spring 2017
- Publications
  - Several Under Development or In-Press
  - A. Leary, V. Keylin, P. Ohodnicki, A. Devaraj, M. E. McHenry, "Stress Induced Anisotropy in Co-Rich Magnetic Nanocomposites for Inductive Applications", Journal of Materials Research, Online In Press, 2016.
  - P. R. Ohodnicki et al, "State-of-the-art of HF Soft Magnetics and HV / UHV Silicon Carbide Semiconductors", PCIM Conference Proceedings 2016, (https://www.vde-verlag.de/proceedings-en/564186197.html)
- Patents
  - Several NETL / CMU Non-Provisional and Provisional Patents Filed

Summary and Conclusions

- Development of 3-Port Converter Based Modular Inverter Topology for Combined Solar PV and ES
- Key Enabling Technologies Include:
  - Wide Bandgap Based Semiconductor Devices
  - High Frequency Nanocomposite Alloy Based Magnetics
- Key Advantages of the Proposed Topology Include:
  - Higher Efficiency Charging of ES Directly from PV Array Through HF Transformer Link
  - Reduced Output Inverter Rating Requirement on DC / AC Stage Relative to PV Array Peak Power
  - Higher Power Densities (2x to 10x) Relative to Separate PV and ES Inverter Topology
  - Equivalent or Improved Reliability Relative to Current Commercial State of the Art
- Preliminary Architecture Studies Demonstrate:
  - Commercial Scale Implementation is Attractive with Commercially Available State of the Art Technology
    - 1.7kV SiC Devices
    - Fe-Based Nanocomposite Cores
  - Utility Scale Implementation Shows Promise for Emerging SiC-Based Devices with 10kV or 15kV SiC Devices
  - Cost of High Frequency Transformer Technology Needs to Be Clarified
- Simulations and Experimental Prototypes to Date Suggest Feasibility of Achieving Technical Targets
- New Capabilities Have Been Established for Developing the Enabling HF Magnetics Technology with Advanced Alloys and Core-Level Engineering Through <u>Advanced Processing at Pilot Scale</u>

Appendix Slides : Assumptions for Architecture Studies of Task 1

Cost Assumptions

- Current 3-phase power electronic converter price is estimated to be **$0.03/W** for both low voltage and medium voltage systems.
- The cost of full bridge is assumed to be **2/3** of a three-phase system, so **$0.02/W .**
- SiC devices are assumed to have **comparable price** with Si in long term
- Line frequency transformer price is **$0.11/W** for 50KVA, and significantly drops to **$0.01/W** for >1MVA
- HF transformer cost is assumed to be **twice** of the line frequency transformer for the same KVA (250KW HF transformer cost is assumed to be $0.08/W, 500KW HF transformer cost is assumed to be $0.04/W)

Power Density Assumptions

- State of the art 3-phase solar inverter power density is **150kW/m^3**
- The power density of a full bridge is assumed to be 1.5 time of 3-phase solar inverter, so **225kW/m^3**
- SiC power converters will have higher power density than Si converters due to reduced cooling requirements and magnetic components. Here assume **1.5 times**.
- Power converter at lower KW is assumed to have similar power density as MV power converter
- Line frequency transformer power density is **19.6kW/m^3** for 50KVA, and significantly increases to **253.1kW/m^3** for >1MVA
- HF transformer power density is **17535.6 kW/m^3** based on calculation
- In power density calculation it is assumed the total power density is the sum of parts

Reliability Assumptions

- Only reliability of power electronic components and transformer are compared
- The MTBF of a Silicon IGBT module (half bridge) is **1,411,654 hours.**
- The MTBF of SiC module is assumed to be **10,000,000 hours** (FIT rate 100 @ 63% rated voltage)
- It is assumed that Silicon IGBT module and SiC modules has similar MTBF for different power ratings.
- The total MTBF is mainly impacted by the individual component MTBF and component numbers
- Redundancy metrics associated with modularity are not included here.