Title of the Proposed Research:

Research on Power Electronics and Control: Grid-Interface for Renewables, Storage and Green Micro-Grids

Related Technology Fields:

The primary area of the proposed research is in the category of "Power Electronics, Power Systems, and Transmission of Electricity". However, the impact of this research will be in all the research areas mentioned in this RFP "Renewable Energy for Minnesota's Future:"

1. Wind Generation
2. Photovoltaic Generation (utility-scale and community-solar)
3. Electric Energy Storage in the form of battery-stacks
4. Hydropower, Biofuels and Thermal Electric, all of which will utilize variable-speed electric generators to optimize their efficiencies at various output power levels
5. Interface of green micro-grids, with significant renewables within them, with each other and with the main grid

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Confidential Information: None

Research on Power Electronics and Control: Grid-Interface for Renewables, Storage and Green Micro-Grids

1. Introduction

Climate change is a grave threat facing humankind and the need for reducing greenhouse gas emissions by using renewables is urgent [1]. The state of Minnesota has ample wind resources in the south-western part of the state and near Rochester [2]. Somewhat surprisingly, solar conditions are also bright in Minnesota in spite of its northern latitude [3]. Renewable sources of electricity are increasing their penetration of the electric utility grid in spite of low oil and gas prices [4]. However, further reducing their cost and increasing their efficiency and reliability will enhance and accelerate their penetration. There is ample room for cost reduction in wind plants by reducing the nacelle weight by 20 percent and in PV plants by reducing the balance-of-system cost which now accounts for two-third and solar cells only one-third of the overall cost [5].

The conventional method of interfacing renewables are based on the use of 60-Hz transformers and silicon devices for the power electronic converters. The goal of this proposed research is to develop a new and improved power-electronics-based interface for interconnecting renewables (PVs and wind turbines), battery storage, and aggregates of these resources, which we term "green micro-grids,'' with the utility grid and with each other.

The proposed interface will have the following novel features: it will be based on a modular topology to render it highly reliable, in conjunction with a high-frequency transformer which can be lighter in weight by a factor of **150** [6], and will utilize advanced wide bandgap semiconductor (silicon carbide and gallium nitride) devices that reduce converter power losses by as much as **80 percent** [7], compared to standard converters using silicon devices. It represents *a breakthrough* at voltages higher than 4.16 kV, which is the limit of existing interface topologies being investigated using high-frequency transformers.

This novel interface has the flexibility to operate at voltages of 4.16 kV to 12.47 kV for community-scale plants but can be scaled up to accommodate higher voltage and power levels, e.g., 34.5 kV that has become a de facto collection grid voltage in utility-scale plants, and at much higher voltages for interfacing green micro-grids. This interface can provide ancillary services and control flexibility to offer "smart" solutions to maintain grid stability even when the penetration of renewables begins to approach conventional sources.

The goal of this three-year project is to have a laboratory prototype built and thoroughly tested in collaboration with our industrial partners so that it serves as the basis for commercializing it in PV/wind and battery-storage applications. Minnesota is poised with several companies such as Cummins (collaborator on this proposal) to capitalize on this research for commercialization. This project will also lead to further research in application-specific topologies. The inherent ability of this interface to exchange power between micro-grids at unequal frequencies and voltage magnitudes is a paradigm shift in controlling low-inertia micro-grids, spawning new research.

2. Present Interfaces using a 60-Hz Transformer and Si-Based Converters:

The present methods of interfacing renewables, based on 60-Hz transformers and converters with silicon devices, are discussed below in wind, PVs and battery-storage applications.

a. Wind-Turbine Interface: To illustrate this, consider Fig. 1 which shows a typical arrangement of components, for example, in a 2.3 MW wind turbine from Siemens [8]. It shows a low-voltage 690-V generator in the nacelle that produces variable-frequency voltages and currents depending on wind speeds, where over two-thousand amperes of current flows through nearly a 100m long cable, thick enough to handle this current. These variable-frequency voltages/currents are converted by the power electronics converter, shown in Fig. 2 by its block-diagram, at the base of the tower to constant amplitude (~700 V) and 60-Hz sinusoidal voltages that are boosted to 34.5 kV by a 60-Hz transformer weighing nearly **7 tons** at these power levels.

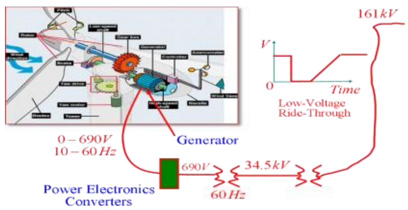

Fig. 1 Components in a typical wind turbine [8].

In a wind plant, now as large as 800 MW [9], hundreds such wind turbines are connected to an underground collection grid at a voltage of 34.5 kV, which has become a de facto collection grid voltage level. Subsequently, another transformer boosts this voltage to 161 kV, for example, for transmission purposes. Some companies are now opting to put the power electronics converter and the 60-Hz transformer in the nacelle so that only a small amount of current needs to be carried by the 100m long cable. But it requires a heavy 7 ton transformer to be located in the nacelle, putting additional burden on the tower structure and the foundation and thus increasing their cost.

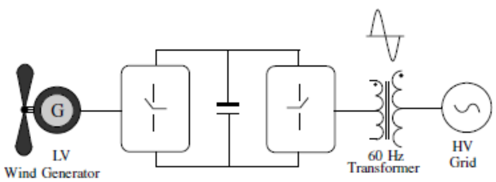

Fig. 2 Power electronics converter with a 60-Hz transformer in a wind turbine.

b. Offshore Wind Plants: Another important application is in offshore wind plants. In such systems, large cost savings are possible by using dc collection systems that will dramatically reduce the part count in the substation. The proposed topology will enable ac and dc collection grids to be combined, as shown in Fig. 3 [10].

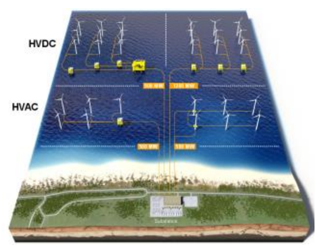

Fig. 3: Offshore wind plants.

c. Photovoltaic Applications: There is substantially larger potential in harnessing electricity using photovoltaics. According to NREL "Solar is Minnesota's single largest energy resource" [11]. Fig. 4 shows a typical topology for a 550 MW PV plant built by First Solar, Inc [12]. It shows that power from a large array of PV modules, each operating at their maximum power point (MPP), is collected at 1,000 V (dc) which is interfaced through a power electronics converter and a 60-Hz transformer to the grid voltage of 34.5 kV.

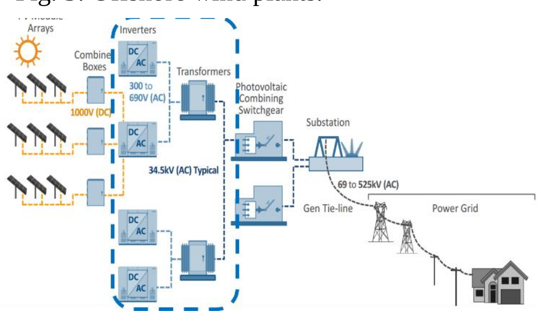

Fig. 4 First Solar Inc.'s 550 MW PV Plant


Fig. 5 Xcel Energy battery facility.

d. Battery-Storage Application: An interface, similar for wind and PVs, but with bi-directional power-flow capability, is used for large-scale battery storage facilities, e.g., Xcel Energy's 1 MW, 7.2 MWh battery facility built in Lavern, MN [13] and shown in Fig. 5.

3. Basis of the Proposed Interface:

The proposed topology and its derivatives are based on the following main aspects: (a) high-frequency (HF) transformers replacing 60-Hz transformers to reduce weight, (b) wide bandgap (WBG) semiconductor devices to improve energy efficiency, (c) a highly modular topology to improve reliability, and (d) elimination of Bearing Currents.

a. High-Frequency (HF) Transformers versus 60-Hz Transformers:

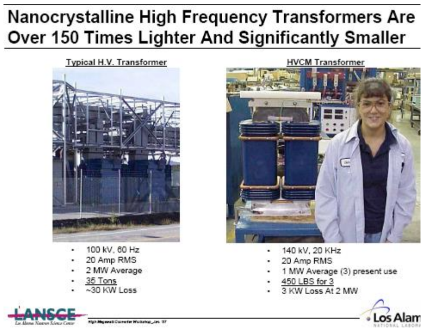

Fig. 6 High Frequency versus a 60-Hz Transformer [6].

Compared to 60-Hz transformers, high-frequency (HF) transformers operating at 20 kHz, for example, can be significantly smaller and lighter by a factor of **150** [6], as depicted in Fig. 6. This size reduction also implies a significant reduction in the amount of copper and the core material needed. The core of HF transformers is made up of a nano-crystalline material such as FINEMET® [14] that is ideal because of its high permeability, high saturation flux-density, and very low core-loss at frequencies of 20 kHz or so at which these transformers are likely to operate at high power-levels. The cost of such material will reduce in large-volume production since no exotic material is required. It is important to note that the losses shown in Fig. 6 in the HF transformer (3 kW) are only one-tenth of those in a comparable 60-Hz transformer (~30 kW). Therefore, it is expected that the overall losses, including those in power electronic converters needed on both sides of the HF transformer, will be lower than in a 60-Hz transformer.

b. Advancements in Power Semiconductor Transistors and Diodes:

There has been a quiet revolution in power electronics led by advancements in wide bandgap (WBG) semiconductor devices such as MOSFETs and diodes. WBG materials such as SiC at high voltages have an order of magnitude faster switching speeds and much lower per-unit conduction voltage drop. These two properties combined result in signification reduction in power losses (by as much as **80** percent) compared to converters made from Si devices, the conventional semiconductor material, as shown in Fig. 7 [7].

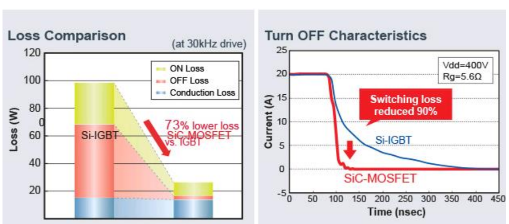

Fig. 7 Loss comparison: Si and SiC converters [7].

SiC-based devices are now commercially available at 1.7 kV and devices at voltage ratings of 10 kV and higher are being tested in laboratories [15]. In high-voltage applications, availability of high-voltage devices avoids the necessity of series-connecting many such devices.

To stimulate research and create new jobs by U.S. semiconductor manufacturers, DOE has funded a 140 million dollar Power America Institute [16] and Governor Cuomo has announced a 500 million dollar effort in the state if New York, led by GE [17]. Vertical-GaN devices being researched will even surpass SiC towards the goal of an "ideal" switch at very high voltages [18]. These developments bode well for the proposed interface, starting now, and more so in the future.

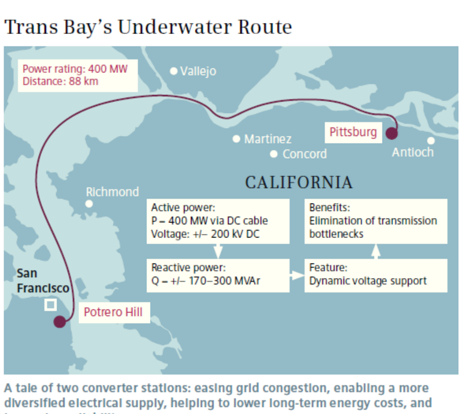

Fig. 8 MMC-based HVDC Trans Bay Project [19].

c. Modular Topology:

The proposed interface is based on the Multi-Modular Converter (MMC) concept commercialized in 2011 in an HVDC Transmission system at +/- 200 kV and 400 MW, as shown in Fig. 8 [19]. Such systems at much higher voltages and 400 power-levels are being designed, confirming that the applicability of the MMC approach extends to very high voltages and power levels.

d. Elimination of Bearing Currents: Switching of common-mode voltages in the PWM-converters on the generator-side in Fig. 2 results in currents through bearings [20], resulting in pitting of bearing as shown in Fig 9. This research proposes to use an open-ended generator to eliminate these bearing currents.

Fig. 9 Pitting of bearings.

4. State-of-the Art in Power Electronic Transformers (PETs) that take advantage of above items:

The reduction in the weight by HF transformers and commercial availability of greatly improved semiconductor devices, have led to research in power-electronic transformers (PETs) that are also referred in research literature as “smart transformers” and “solid-state transformers”. MIT Technology Review ranked it as one of 10 breakthrough technologies in 2011 [21].

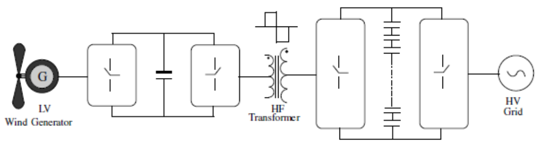

Fig. 10 Block diagram of “Conventional PET”.

Fig. 10 shows the block diagram of the PET, termed here as the “Conventional PET,” being investigated at NSF’s Engineering Research Center at NCSU [22].

Limitations of “Conventional PETs” [23-24]: It has some serious limitations described as follows for extending its application beyond 4.16 kV to 34.5 kV voltages that have become de facto collection-grid voltages in wind and large-scale solar plants: (a) semiconductor devices and capacitors need to be connected in series, causing addition losses in the circuitry needed to make them share blocking-voltages equally, (b) converters are controlled by pulse-width-modulation (PWM) which results in the hard-switching of semiconductor devices, causing switching power losses in them, (c) the high-frequency transformer is subjected to high dV/dt (rate of change of voltage), severely stressing the transformer insulation and causing Electro-Magnetic Interference (EMI), which can deal to spurious signals and failures in the control circuitry, (d) the harmonics in voltages/currents at the multiples of the switching-frequency result in additional power losses in the transformer core and the windings, and (e) it is not modular and hence reliability is a concern.

5. Proposed MMC-based “Modular-PET”:

Our research group was first to see the application of MMCs for PETs, have published numerous papers [25-27], and our university has filed a utility patent [28].

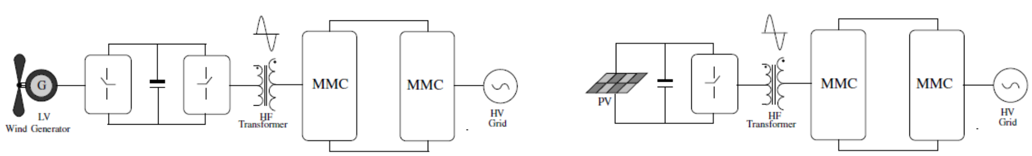

Fig. 11 Proposed Modular-PET (a) wind-generation; (b) PVs.

Using Modular-PET, the block diagram of a wind-electric system is shown in Fig. 11a and for interfacing PV plants in Fig. 11b. MMCs in Fig. 11a,b consist of a series of submodules as shown in Fig. 12a, where each submodule itself consists of a charged-capacitor, as shown in Fig 12b, which can be inserted or bypassed by the semiconductor switches, thus resulting in two voltage levels. By appropriately inserting or bypassing the MMC submodules, a sinusoidal voltage can be synthesized at the ac output of the PET.

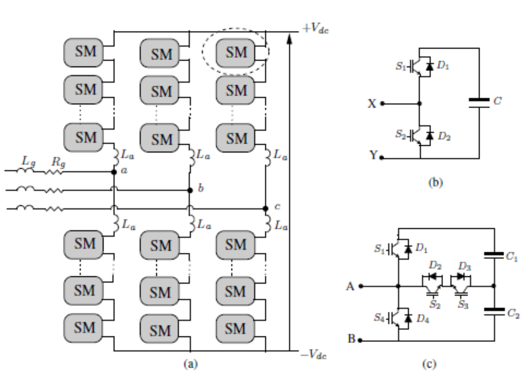

Fig. 12 (a) series connection of submodules; (b) 2-level; (c) 3-level submodule [27]

A simple modification is proposed to provide three voltage-levels for v_{AB} by using 1/3rd and 2/3rd capacitances, and connecting the mid-point of the two capacitors through another switch, as shown in Fig. 12c. To obtain the same number of steps in the ac-side voltage being synthesized (ideally sinusoidal), the three-level submodule in comparison will result in the following benefits: half the number of submodules resulting in lower overall system footprint and higher efficiency with reduced conduction and switching losses

Compared to the "conventional" approach, the proposed Modular-PET has the following advantages: (a) series-connection of semiconductor devices and capacitors is not required, (b) intelligent commutation results in majority of switching transitions to be soft-switched, thus eliminating switching-losses associated with hard-switching, (c) the high-frequency transformer voltages are nearly sinusoidal, thus very low dV/dt in comparison, reducing the stress on transformer insulation and resulting in much reduced EMI, (d) the transformer voltages and currents, being nearly sinusoidal, result in much lower power losses in the transformer core and transformer windings, respectively, (e) its modular structure allows a lineup of spare submodules, resulting in much higher reliability, and (f) this technology has been in operation for HVDC applications at much higher voltages (200 kV) and hence can easily apply at 34.5kV and at higher voltages for interfacing green micro-grids to the main grid.

A proof-of-concept laboratory hardware in its initial stages is shown in Fig. 13a, and the voltage and current waveforms are shown in Fig. 13b.

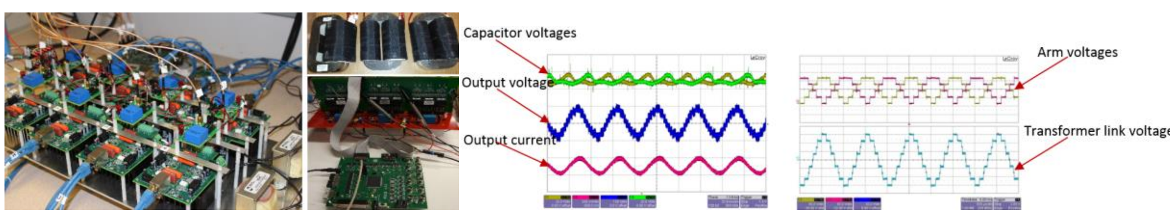

Fig. 13: (a) Experimental hardware; (b) Waveforms

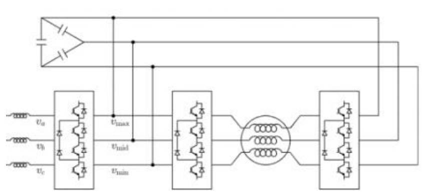

Fig 14 Open-ended drive [29-30].

Elimination of Bearing Currents [29-30]: In this proposed interface, an open-ended drive shown in Fig. 14 will be investigated to eliminate the problem of bearing currents mentioned earlier. The basic concept with 60-Hz supply is protected by a UMN patent [30].

6. Ancillary Services:

This interface should be able to provide the following ancillary services at each unit, as well as at the plant level: real power control, reactive power and voltage control, governor frequency response, power scheduling and ramp-rate control, controlled inertial response, Low-voltage ride-through, etc. These services are provided by traditional fossil-fuel driven generation sources and at high levels of penetration, electricity generated by renewables must also be able to provide these services for system stability and to make renewable sources economically competitive with traditional generation sources [31]. The challenge with renewable-interfaced generation is the lack of mechanical inertia. Therefore, feedback control and optimization become critical to realize ancillary services from renewables.

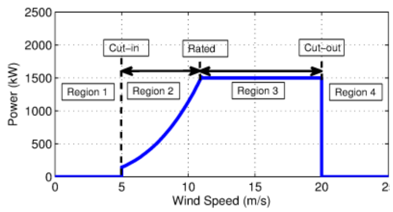

Fig. 15 Turbine Operating Regions.

Advanced control of wind turbines to deliver ancillary services [32-39]: In any wind turbine, the control of the blade pitch-angle and that of the power electronics interface have to be coordinated. It is proposed to use gain scheduling to operate the turbine anywhere within the power envelope shown in Fig. 15. Providing ancillary services requires modulation of the power generated by the turbine. In other words, the turbine does not necessarily operate at the peak efficiency C_p^* as is traditionally done at low wind speeds. The turbine can reduce the power coefficient to a new value $C_p < C_p^*$ by changing the blade-pitch angle and/or the tip-speed ratio. The desired C_p can be obtained by a combination of the blade pitch-angle and the tip-speed ratio. This enables a secondary performance objective to be achieved, e.g. stored kinetic energy, reduced structural loads, etc. Roughly, the control algorithm can be designed to provide ancillary services by extracting kinetic energy from the rotating blades in the short term. This must be done carefully to avoid large structural loads. The goal of this research task is to design the turbine control algorithm and implement it on the interface proposed in this research.

7. Interconnection of Micro-Grids to the Main Grid:

It is highly probable that the grid of the future will be composed of a collection of green micro-grids, where electricity generated by renewables and aided by storage, aggregated with the power supplied by the main grid, will meet the internal load. Also, in such micro-grids it is often the case that the demand and supply for power are relatively closely matched (by design) when compared to the conventional grid. Thus it is quite possible to have large deviations from the grid frequency ---driven by power imbalances---where it is difficult to meet current grid standards on frequency.

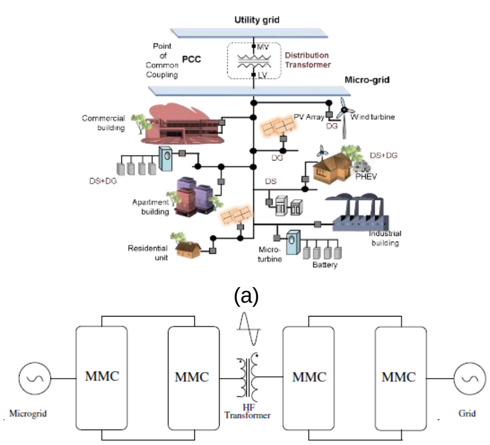

Fig. 16 (a) conventional; (b) proposed interface.

Unlike the requirement with a traditional interconnection shown in Fig. 15a, the proposed interface shown by a block diagram in Fig. 15b will allow low-inertia micro-grids to operate at voltages and frequencies that are different from each other while exchanging regulated power between themselves and the main grid. Just like the low-voltage ride through conditions in interfacing renewables, it will have the ability to remain connected under adverse conditions in support of the overall system stability. In this context, the role of the proposed interface is critical since it will facilitate seamless plug and play functionality of micro-grids with each other and to the grid by negotiating the mismatch in the operating conditions of the micro-grids and the grid at relevant time scales.

For example, the grid voltage at the main-grid side may be, e.g. 34.5 kV, and at the micro-grid side 12.47 kV. In such an application, the proposed interface can be considered a "smart" transformer through which, unlike the conventional transformer, the power flow can be controlled and the frequency at the micro-grid side can be other than the frequency of the main-grid, as a signal for the generation and the load within the micro-grid to respond appropriately to bring its frequency back to that of the main-grid frequency.

The grid in this scenario serves as a safety net for the micro-grids; however, the micro-grid will need to provide ancillary services to the grid when demanded. Under proposal goals, we will demonstrate the proof-of-concept for the ability of smart transformer as being effective for interfacing micro-grids and the grid with plug and play capability. Furthermore we will synthesize algorithms and architectures for coordinated response of multiple micro-grids for ancillary services to the grid including contingency events leveraging the smart transformer capabilities. This will require encoding ancillary-services objectives into control objectives that will then be realized with state-of-the-art feedback control schemes at the PETs.

In the recent decade substantial progress was achieved in incorporating multiple and diverse objectives in controller design in a systematic manner. With reference to the proposed interface, there are multiple objectives that need to be targeted. For instance, the response time to changes in frequency on either side of the transformer has to be minimized, the inaccuracies in the sensors have to be managed, power flow desired has to be matched by the actual power flow with desired time constants. Under proposal objectives multi-objective and multivariable control strategies pioneered by PIs (see [40] and [41]) will be used to enhance the performance of the smart transformer proposed. The control strategy also lends itself to a diagnostic tool, where the control effort in regulating the target (for example a set-point frequency) provides a measure of the state of the system. Such a diagnostic tool can be used by the microgrid to rapidly sense the condition of the grid. Thus a contingency event faced by the grid can be sensed in a timely manner and an automated response of providing power to the grid (due to sudden frequency collapse on the grid for example) can be triggered by micro-grids attached to the grid. The same principle can be used to facilitate low voltage ride through (LVRT) for wind plants where reactive power can be provided to the grid [42]. Here we will devise advanced control methods based on multi-objective and multivariable control methods discussed above, and associated diagnostics that will enhance operation efficiencies while providing critical contingency support in an automated manner.

The smart transformer will allow for a seamless means for distributed energy consumers and producers to interface and interact with each other and the grid. A stable operation of the grid needs to be guaranteed which is increasingly challenging with the flexibility of engaging and disengaging micro-grids. Here essential to provide a coordinated response to requests by the grid or its representative say an aggregator. In this scenario, an aggregator would be the authority that coordinates and oversees the operation and interaction of clusters of micro-grids. The aggregator would provide a schedule of ancillary services needed and the distributed micro-grids when aggregated should meet the service demand. Under proposal goals we will devise strategies to disambiguate aggregated service schedule demanded by the aggregator into feasible schedules that satisfy local constraints (e.g., generation capacities) of participating micro-grids. The feasible schedules to be met by each of the micro-grids in terms of reference powers to be provided by the micro-grids to the aggregator will then be used as input to the control algorithm for the smart transformer to execute the local schedule. The task above has two steps; one of obtaining feasible schedules and the other of realizing the schedule. We will utilize recent efforts by PIs (see [43]) and others, (see [44]) for parametrizing all feasible schedules. The local feasibility schedule will rely on forecasted data; strategies on how to handle mismatch of the actual conditions from those assumed while devising the schedules will be developed for multiple temporal scales.

Toward achieving the objectives above we will simulate a test-bed environment where microgrid prototypes will be interfaced with the smart transformer for evaluating methods to be developed. Here micro-grids with different operating frequencies and voltages will be instantiated. The integrated platform will allow easy prototyping of algorithms. In particular, this phase of the research will allow us to investigate how ancillary services can be realized at the level of the PETs and experimentally verify the same. The realization of micro-grid prototypes will be realized with existing funding; the focus of the effort here is to evaluate the performance of the smart transformer when used to interconnect micro-grids and microgrid to the grid.

8. Research Tasks and Deliverables:

Major research tasks and deliverables are as follows:

1. Analysis, design, fabrication and testing of Modular PET: In the laboratory a modular PET will be built and tested at the limit of the capability of our laboratory. It will be built at a 5 kW power level with the ac-side voltage of 208 V (L-L) and the dc voltage of 400 V. It will be built using SiC wide band gap devices. Various tasks and deliverables associated with this are as follows:
    a. Complete the testing of the MMC with 2-level and 3-level submodules for grid frequency (60 Hz) and high frequency (20 kHz) operation. This will include validating the MMC modulation, commutation, voltage balancing and circulating current control.
    b. Complete testing of Modular PET integrating MMC, high frequency transformer and low side converter, as shown in Fig. 11.
    c. Analyze and simulate various ancillary services like operation under unbalance voltages, reactive power and voltage support, frequency regulation and low-voltage ride-through and test them on the fabricated hardware prototype.
2. Design of high-frequency transformers at high voltages: Using finite element analysis tools, develop a design procedure for loss and leakage inductance optimization.
3. Analysis, design, fabrication and hardware testing of open-end winding drive for eliminating bearing currents
    a. Complete the testing for 3-level open-end winding drive based on matrix converter for elimination of bearing currents supplied by 60-Hz grid voltages.
    b. Integrate this 3-level open-end winding drive within the PET.
4. Research in application-specific topologies such as modular but unidirectional-power topologies suited for PVs and only permanent-magnet wind generators that will be compared with the proposed modular-PET topology while providing the ancillary services.
5. Analyze and simulate advanced control of wind turbines to deliver ancillary services that will be tested with the hardware being developed under Task 1c.
6. Control of green micro-grids with the main grid and with other micro-grids:
    a. Advanced control, automated sensing of grid conditions and response by micro-grids to contingency events
    b. Planned coordinated response of micro-grids to provide ancillary grid services
    c. A test-bed for Micro-grids interfaced with each other and to the grid using the smart transformer simulated in software

9. Project Management Plan:

Year-to-year milestones associated with various research tasks and deliverables are as below. Results of these tasks and any deviation from the completion date will be explained in the report submitted.

Task		Year 1	Year 2	Year 3
1	a	x	x	
	b	x	x	x
	c	x	x	x
2		x	x	x
3	a	x	x	
	b		x	x
4		x	x	x
5		x	x	x
6	a	x	x	x
	b	x	x	x
	c	x	x	x

10. Proposal Review Metrics:

1. Scientific and Technical Merit

The proposed Modular-PET represents a breakthrough in interfacing renewables and micro-grids at voltages higher than 4.16 kV, which is the limit of existing PET topologies such as the one being investigated at NSF's Engineering Research Center (ERC) at NCSU [22]. This novel interface can be scaled up to accommodate various voltage and power levels, e.g., 34.5 kV that has become de facto collection grid voltage in utility- and community-scale renewable/storage plants. It will result in substantial increase in the overall system efficiency, reliability, and lower cost. Being an interface, it applies to all the renewable electricity fields identified in this RFP.

It is proposed to develop a small-scale prototype at 5-KW and 400 V (the limit of our laboratory capability) that demonstrates all the attributes such as providing ancillary services that a commercial-scale unit will need, in order to rapidly scale it up.

The ability of this interface to exchange regulated power between micro-grid and the grid, while at unequal frequencies and voltage magnitudes is a new paradigm in control of micro-grids which will be developed.

2. Commercial Impact:

There is a growing statewide, national and international market. The fundamental concepts of the proposed interface are covered in our university's pending utility-patent [28]. It is envisioned that several new patents on implementation will emerge during this project. The IP protection offered by these patents will be an inducement to any company interested in commercializing such an interface. Minnesota has several companies that will be approached in addition to Cummins Power Generation, a collaborator on this proposal, for possible commercialization.

3. Collaboration and Institution Partnership:

A team of researchers with synergistic interests has been assembled to bring this research project to fruition within a three-year period. It includes Ned Mohan and Bill Robbins from ECE on the power-electronics aspect of this project, and Prof. Peter Seiler from AEM to guide in meeting ancillary services in wind turbines. Dr. Chris Henze located in Lakeville, MN will provide consultation in building the hardware, based on his over 30 years of industrial experience in developing commercial-grade prototypes, with an eye towards scaling it up for commercialization purposes. Our partners from Cummins, Brad Palmer and Dakshina Murthy-Bellur, will guide our research so that it conforms to what will be needed in a utility/community-scale interface and possible market development as this research is ongoing. Professors Murti Salapaka and Sairaj Dhople from ECE are at the forefront of research in control, through funding from NSF, DOE, ARPA-E and other agencies, to guide an entirely new paradigm in controlling the interconnection of green micro-grids. Prof. Daniel Opila from the US Naval Academy has a great deal of industrial experience prior to joining USNA. He will guide this research project to make sure that the proposed interface meets the ancillary service requirements of renewables/storage.

4. Obtaining Other Funding:

Having a company such as Cummins as one of our partners, this research will result in continued collaboration with Cummins. Professors Murti Salapaka and Sairaj Dhople will use the results from this project as an important part of preliminary evidence for seeking funding from federal agencies such as the DOE, ARPA-E and NSF.

Prof. Dan Opila is very familiar with the requirements for the solid-state substations for electric ships and submarines in the Navy that is actively investigating power systems with main distribution voltages of 4-10kV AC and 10-20kV DC, similar to the collection grid in wind and PV plants. Therefore, the technology development, mass production, and low-cost of the renewables arena provides a valuable commercial counterpart to the Navy's requirements. The research carried out can lead to continuing research funding for applications in the Navy.

Power America Institute will be approached in realizing the full potential of wide band gap devices, e.g., their capabilities to operate at very high temperatures, in various applications.

<u>Educational Dissemination</u>:

The results of this research will be disseminated through the Consortium of Universities for Sustainable Power (CUSP™ - www.cusp.umn.edu [45]) where, in addition to 13 graduate courses related to power and power electronics already developed, we are developing 6 more courses through ONR funding for a total of 19 graduate courses. Based on these, our College of Continuing Education is considering to offer a master's degree to practicing engineers.

<u>Budget</u>:

Approximately 250,000 dollars per year to support 1 post-doc, 4 graduate students and estimated laboratory supplies; consultation time of Dr. Chris Henze at $90/hour. No major equipment will be purchased and no faculty salaries are requested. Travel expenses to attend conferences and present papers will be supported by other funds that PIs have.

								Period 1	Period 2	Period 3	Cumulative
							months	12	12	12	36
	annual salary	monthly fringe	fringe rate	tuition	months	no. of students	hours				
POSTDOC	$ 40,000	747	0.2240		12	1	Salary	$ 40,000	$ 40,800	$ 41,616	$ 122,416
(12 months; 100% time)							Fringe	$ 8,960	$ 9,139	$ 9,322	$ 27,421
								$48,960	$49,939	$50,938	$149,837
RA	$ 19,882	389	0.1760	13,915	9	4	Salary	$ 81,119	$ 82,741	$ 84,396	$ 248,256
hourly rate	$ 25.49						Fringe	$ 14,277	$ 14,562	$ 14,854	$ 43,693
(acad = 9 months; 50% time)			hours	780			Tuition	$ 55,660	$ 55,660	$ 55,660	$ 166,980
			tuition per AY hour	$17.84				$151,056	$152,963	$154,910	$458,929
RA	$ 6,627	389	0.1760	4,638	3	4	Salary	$ 27,038	$ 27,579	$ 28,131	$ 82,748
(smr = 3 months; 50% time)							Fringe	$ 4,759	$ 4,854	$ 4,951	$ 14,564
			hours	260				$31,797	$32,433	$33,082	$97,312
TOTAL SALARIES/FRINGE								***$ 231,813***	***$ 235,335***	***$ 238,930***	***$ 706,078***
LAB SUPPLIES								$ 10,000	$ 4,500	$ 4,000	$18,500
CONSULTANT								$ 8,000	$ 10,000	$ 7,000	$25,000
TOTAL COSTS								**$249,813**	**$249,835**	**$249,930**	**$749,578**

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3. National Renewable Energy Laboratory, "Photovoltaic Solar Resources of the United States", http://www.nrel.gov/gis/images/eere_pv/national_photovoltaic_2012-01.jpg
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5. Steve Campbell, "Photovoltaics Outlook", NSF/NAE-Sponsored Faculty/Industry Workshop on Reforming Electric Energy Systems Curriculum with Emphasis on Sustainability, April 9-10, 2015, http://cusp.umn.edu/assets/DC_Workshop_2015/Campbell_PV_Day1.pdf
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18. Isik C. Kizilyalli, "Vertical Power Electronic Devices Based on Bulk GaN Substrates", NSF/NAE-Sponsored Faculty/Industry Workshop on Reforming Electric Energy Systems Curriculum with Emphasis on Sustainability, April 9-10, 2015, http://cusp.umn.edu/assets/DC_Workshop_2015/Kizilyalli_Avogy_Day2.pdf
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26. Sahoo, A.K.; Mohan, N., "High frequency link multi-winding power electronic transformer using modular multilevel converter for renewable energy integration," in *Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE* , vol., no., pp.4642-4648, Oct. 29 2014-Nov. 1 2014
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45. "Consortium of Universities for Sustainable Power", University of Minnesota, Twin Cities, http://cusp.umn.edu/

CVs of the Principal Researchers

Curriculum Vitae of Professor Ned Mohan (www.ece.umn.edu/~mohan)

Personal

U.S. Citizen (naturalized; born in India); married with two children

Education

1973 University of Wisconsin - Madison, Electrical Engineering, Ph.D.

1972 University of Wisconsin – Madison, Nuclear Engineering, MS

1969 University of New Brunswick (Canada), Electrical Engineering, MS

1967 Indian Institute of Technology, Electrical Engineering, B. Tech

Professional Work

1973-1975 University of Wisconsin - Madison: Post-doc

1976-Present University of Minnesota – Twin Cities

- 1976 – 1981 Assistant Professor
- 1981 – 1990 Associate Professor
- 1991 – Present Professor

Awards and Recognitions

2014 Elected to the National Academy of Engineering (NAE)

2014 IEEE Nari Hingorani FACTS Award - IEEE Power & Energy Society 1982 Young Engineer of the Year – IEEE Twin Cities Section

2014 Outstanding Contributions to Postbaccalaureate, Graduate, Professional Education Award - University of Minnesota

2013 Innovative Program Award - U.S. ECE Department Heads Association

2012 Ramakumar Renewable Energy Excellence Award - IEEE Power & Energy Society

2011 Distinguished Alumnus Award - Indian Institute of Technology, Kharagpur (India)

2010 IEEE Undergraduate Teaching Award

2010 Utility Wind Integration Group Achievement Award

2008 IEEE-PES Outstanding Power Engineering Educator Award

2007 Morse-Alumni Distinguished Undergraduate Teaching Award – Univ. of Minnesota

1998 The George Taylor I. T. Distinguished Teaching Award, University of Minnesota

1991 Visiting Erskine Fellowship, University of Canterbury, New Zealand

1996 Fellow of the IEEE

1993 Oscar A. Schott Professorship of Power Electronics and Systems (continuing) - UMN

Primary Research Focus: Sustainability - Interfacing renewable energy sources with the utility grid to increase their penetration; increasing energy-efficiency of usage of electricity; energy storage making Power Systems more robust and reliable

Primary Education Focus: Sustaining the national infrastructure in the area of electric power and energy by revitalizing the curriculum and disseminating it widely by online graduate courses; increasing the pipeline of students from community colleges and high schools to this field.

Textbooks (translated into a total of 8 languages):

1. Power Electronics: Converters, Application and Design by Mohan, Undeland and Robbins. Published by Wiley, 1989. 2nd edition in 1995. 3rd edition in 2003 (Translated to Chinese, Greek, Italian, Korean, Spanish and Turkish).
2. Power Systems published by N. Mohan, published by Wiley, 2012 (Translated to Portuguese)
3. Electric Machines and Drives by N. Mohan, published by Wiley, 2011 (Translated to Portuguese)
4. Power Electronics by N. Mohan, published by Wiley, 2011 (Kazak, Portuguese; being translated to Korean).
5. Advanced Electric Drives: Analysis, Control and Modeling using Simulink® by N. Mohan, published by Wiley 2014

Intellectual Property: 19 U.S. patents issued; 2 applied and pending

Graduate Students: Over 170 graduate students including 38 PhDs graduated, present group consists of 8 PhDs and 2 MS students

External Support: Past, present and pending; over 16.5 million dollars during 2000-2015

Technical Publications: Over 350 Technical Articles

Laboratory Setups Developed and Commercialized through Third parties: 2 (These setup can now be purchased from Digi-Key, http://www.vishay.com/landingpage/universityproducts, for easier accessibility)

Tutorials at Major Conferences: 29 tutorials including 18 at major annual conferences of the IEEE

Internet-based Short Courses Taught to Practicing Engineers: 8

NSF/ONR-Sponsored Faculty Workshops for Dissemination: 28

Organized Workshops on Renewable/Wind Energy: 4

NSF-REU, NSF-RET: interacted with several students and teachers

University Service: Distinguished McKnight University Professor Selection Committee; President's Distinguished Faculty Mentor; Chaired George W. Taylor Awards for Teaching, Research and Service; University Sustainability Committee; Scientific Advisory Committee: University Climate Action Plan; Hosted one of the earliest Chinese Scholars at UMN (Prof. Wang - Jilin University); Co-Chair of the Academic Committee of the India Center Initiative

External Program Reviews: Colorado School of Mines, Golden, CO, 2005– Review of Engineering Program; Purdue University, April 10-11, 2006 – Review of Electrical Engineering Program; Iowa State University – April 30, 2015

Establishment of Center for Electric Energy in 1981: Participation by 7 regional electric utilities

Courses Taught and Created for CUSP™: www.cusp.umn.edu

Courses and Master's Degree Proposed and Accepted:

1. EE 2701 "Sustainable Electricity: Renewables and Conservation" – developed and I will be teaching it starting in Spring 2016; LE Theme of Technology and Society approved
2. EE 1000-Level "Energy from Renewables: Envisioning a Brighter Future" – has been approved by the ECE Curriculum Committee
   - Workshop organized to develop this course to a "College in the Schools" program on April 16, 2016 to which all high school science teachers from MN will be invited; funding of $11,500 has been obtained and a proposal for addition $9,750 is pending.
3. Master's Degree "Master of Electric Power and Power Electronics Engineering" – Based on 19 graduate courses, 13 developed and 6 others to be developed by ONR funding, our college of Continuing Education is considering to offer an online master's degree aimed at practicing engineers. The Dept of Electrical and Computer Engineering has voted the approval of this consideration.
   - In the NSF-funded workshop organized for July 6-8, 2016, the plan to offer this master's degree, if decided to offer by the College of Continuing Education, will be announced at this workshop to practicing engineers and ECE faculty nationwide.

Community Service:

1. Weekly (every Saturday) presentation on unity and connectedness of all
2. Presentations in high schools in their World Cultures and Religions classes
3. Help with new Americans (Bhutanese Refugees)
4. Educator Workshop organized by the UMN Institute for Global Studies on March 1, 2016

BIOGRAPHICAL SKETCH

William P. Robbins
Professor and Associate Head of Electrical and Computer Engineering
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Tel: (612) 625-8014 Fax: (612) 625-4583 Email: robbins@umn.edu

Education

Ph.D., 1971, University of Washington, Electrical Engineering
M.S., 1965, M.I.T., Electrical Engineering
B.S., 1963, M.I.T., Electrical Engineering

Research and Professional Experience

Associate Head, Dept. of ECE, Univ. of Minn. 2007 -
Professor, Dept. of Electrical Eng., Univ. of Minn., 1991-
Associate Prof., Dept. of Elect. Eng., Univ. of Minn.,1975-1991
Assistant Professor, Dept. of Elect. Eng., Univ. of Minn., 1969-75
Associate Staff Member, Boeing Scientific Research Laboratories, Seattle, Wash., 1967-69
Research Engineer, Boeing Co., Seattle, Wash., 1965-67

Relevant Publications:

1. Power Electronics: Converters, Applications, and Design,, 3nd Edition, Ned Mohan, Tore Undeland, and W.P. Robbins, © 2003, published by John Wiley and Sons, ISBN 0-471-22693-9

2. Ned Mohan, William P. Robbins, and Bruce F. Wollenberg, " Power System Education Based on CUSP™ Curriculum", IEEE Trans. on Power Systems, Vol. 29, No. 4 (July 2014), p. 1896

3. William P. Robbins and Ned Mohan, "Power Semiconductor Device Education: Which Topics and What Depth": Electro-Chemical Society Fall 2013 Meeting, San Francisco, CA. Oct. 28-31, 2013, ECS Transactions, Vo. 58, No.4, p.237-244

4. Iyer, K.; Robbins,W.; Basu, K.; Mohan, N., "Transformer Winding Losses with Round Conductors for Duty-Cycle Regulated Square Waves"' Published in IEEE International Power Electronic Conference (IPEC), May 2014

5. Ned Mohan, William P. Robbins, Paul Imbertson, Tore M. Undeland, Razvan C. Panaitescu, Amit Kumar Jain, Philip Jose, and Todd Begalke, "Restructuring of First Courses in Power Electronics and Electric Drives That Integrates Digital Control", IEEE Trans. on Power Electronics, Vol. 18, No. 1, pp. 429-437, Jan. 2003

Synergistic Activities

1. Co-PI of DOE grant OE000427: A Nationwide Consortium of Universities to Revitalize Electric Power Engineering Education by State-of-the-Art Laboratories: administrator of grant involving some 80 universities. 2010-2014

2. Co-organizer (with Ned Mohan) and participant of over 20 faculty workshops sponsored by ONR, NSF, DOE, and EPRI to disseminate UMN-developed electric energy systems curriculum.

3. Co-developed the first instructional laboratories offered at the University of Minnesota in MEMs fabrication and power electronics.

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Electrical and Computer Engineering Department, University of Minnesota, Twin Cities,

Education and Training

Indian Institute of Technology, Madras	B.Tech.	Mechanical Engineering	1991
University of California, Santa Barbara	MS	Mechanical Engineering	1993
University of California, Santa Barbara	PhD	Mechanical Engineering	1997

Employment History

1997-2003	Assistant Professor	Electrical and Computer Engineering Dept. Iowa State University
2001-2006	Chair	Control Systems Group Electrical and Computer Engineering Department Iowa State University
2002-2003	Litton's Industries Chair	Electrical and Computer Engineering Dept. Iowa State University
2003-2007	Associate Professor	Electrical Engineering Dept. Iowa State University
2007-2010	Associate Professor	Electrical and Computer Engineering Department University of Minnesota, Minneapolis
2010-present	Professor	Electrical and Computer Engineering Department University of Minnesota, Minneapolis
2013-present	Chair	Vincentine Hermes-Luh Chair, University of Minnesota, Minneapolis
2013-2014	Hardware Engineer	Google Inc. (via Adecco)

Awards

Dean's fellowship for outstanding graduate performance, University of California, Santa Barbara, 1992, CAREER Award, 1998; National Science Foundation, ISU, Young Engineering Faculty Research Award, 2001; Keynote Lecture, "Control and Systems Approaches to Atomic Force Microscopy",International Federation of Automatic Control (IFAC), 17th IFAC World Congress, July 6-11, 2008, Seoul, Korea; Plenary Lecture, ``Real-time interrogation of material properties at the nanoscale**",** New Trends and Challenges in Modeling and Control of Microsystems, µControl'12, Besancon, France, May 31st-June 01, 2012; Expert Talk: "Real-time probe based quantitative determination of material properties at the nanoscale", 5th Multifrequency AFM conference, Spain Madrid, June 16th-17th, 2014; Several papers awarded as best paper in session at the American Control Conference.

10 peer-reviewed publications demonstrating capability in the broad field

1. M. V. Salapaka, M. Dahleh, and P. Voulgaris, "Mimo optimal control design: the interplay of the H2 and the l1 norms", IEEE Transactions on Automatic Control, V43, no. 10:pp.1374-1388, October 1998.
2. M. V. Salapaka, M. Khammash, M. Dahleh, "Solution of MIMO H2/l1 problem without zero interpolation", SIAM Journal on Optimization and Control, V37, no. 6, pp.1865-1873, 1999.

3. M. Khammash, M.V. Salapaka, T. VanVoorhis,"Robust Synthesis in l1: A globally optimal solution", IEEE Trans. Automatic Control, Volume: 46 Issue: 11 , Page(s): 1744 -1754, Nov. 2001.
4. Qi, Xin, Mustafa H. Khammash, and Murti V. Salapaka. "A matlab package for multiobjective control synthesis." In Decision and Control, 2001. Proceedings of the 40th IEEE Conference on, vol. 4, pp. 3991-3996. IEEE, 2001.
5. Xin Qi(s), M. V. Salapaka, Petros G. Voulgaris and Mustafa Khammash, "Structured optimal and robust control with multiple criteria: A convex solution", IEEE Trans. Automatic Control,49 (10) pp 1623-1640, October 2004.
6. V. Yadav(s), **M.V. Salapaka**, P. G. Voulgaris, "Architectures for Distributed Controller with Sub-controller Communication Uncertainty" IEEE Trans. Automatic Control, Vol. 55, Issue 8, pp. 1765-1780, July 2010.
7. D. Materassi, M. V. Salapaka, "A Generalized Zames-Falb Multiplier", IEEE Trans. Automatic Control, Vol. 56, no. 6, pp: 1432-1436, June 2011.
8. D. Materassi, M. V. Salapaka , "On the problem of reconstructing an unknown topology via locality properties of the Wiener filter", IEEE Trans. Automatic Control, 57(7):1765-1777, 2012.
9. Materassi, D., Innocenti, G., Giarre, L., Salapaka, M.," Model identification of a network as compressing sensing", Systems & Control Letters, vol:62, no:8, pp:664-672, 2013.
10. S Salapaka, B Johnson, B Lundstrom, S Kim, S Collyer and Murti Salapaka, "Viability and analysis of implementing only voltage-power droop for parallel inverter systems", Control and Decision Conference, Los Angeles, CA, pp:3246-3251, December 15-17, 2014

Other peer-reviewed publications demonstrating capabilities in the broad field

1. M Wytock, S Salapaka, M. V. Salapaka, "Preventing Cascading Failures in Microgrids with One-sided Support Vector Machines", Control and Decision Conference, Los Angeles, CA, 2014
2. Materassi, Donatello, Salapaka, Murti V, "Network reconstruction of dynamical polytrees with unobserved nodes", IEEE 51st Annual Conference on Decision and Control (CDC), vol:, no:, pp:4629-4634, 2012
3. Donatello Materassi, Murti V. Salapaka, "Reconstruction of directed acyclic networks of dynamical systems", American Control Conference (ACC), 2013, vol:, no:, pp:4687-4692, 2013
4. M. Sridharan, A. Somani, M. V. Salapaka, "Approaches for Capacity and Revenue Optimization in Survivable WDM Networks", Spl. Issue on Survivable Optical Networks, Journal of High Speed Networks, August 2001. vol. 10, no. 2, pp. 109 -125,
5. M. Sridharan, M. V. Salapaka, A. Somani, "A Practical Approach to Operating Survivable WDM Networks", Special Issue on WDM Based Network Architectures, IEEE Journal on Selected Areas in Communications on WDM-based Network Architectures. vol. 20, no. 1, January 2002.
6. S. Salapaka, A. Sebastian, J. P. Cleveland and M. V. Salapaka, "High Bandwidth Nano-positioner: A Robust Control Approach", Review of Scientific Instruments, Vol. 73, no. 9, pp. 3232-3241, 2002.
7. M. V. Salapaka, P. Voulgaris, and M. Dahleh, "Controller design to optimize a composite performance measure", Journal of Optimization Theory and Applications, V91, no. 1:pp. 91-113, October 1996.

Peter J. Seiler, Biographical Sketch

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Professional Preparation

University of Illinois, Urbana-Champaign	Mechanical Engineering	B.S. 1996
University of Illinois, Urbana-Champaign	Mathematics	B.S. 1996
University of California, Berkeley	Mechanical Engineering	Ph.D. 2001

Professional Experience

2011-	Assistant Professor, Aerospace Engineering and Mechanics, University of Minnesota.
2008-2011	Research Associate, Aerospace Engineering and Mechanics, University of Minnesota.
2004-2008	Senior Research Scientist, Honeywell Labs, Honeywell.
2002-2004	Assistant Professor, Mechanical and Industrial Engineering, University of Illinois, Urbana-Champaign.
2002-2002	Post-doctoral Researcher, Mechanical Engineering, University of California, Berkeley.

Products Related to Proposed Project:

1. E. Bitar and P. Seiler, “Coordinated Control of a Wind Turbine Array for Power Maximization,” American Control Conference, p.2904-2913, 2013.
2. A. Ozdemir, P. Seiler, and G.J. Balas, “Design Trade-offs of Wind Turbine Preview Control,” IEEE Control Systems Technology, vol. 21, no. 4, p.1143-1154, 2013.
3. A. Ozdemir, P. Seiler, and G.J. Balas, “Performance of Disturbance Augmented Control Design in Turbulent Wind Conditions,” Mechatronics, Special Issue on Past, present and future modeling and control of wind turbines, vol. 21, no. 4, p.634-644, June 2011.
4. S. Wang and P. Seiler, “Gain Scheduled Active Power Control for Wind Turbines,” AIAA Atmospheric Flight Mechanics Conference, AIAA 2014-1220, 2014.
5. J. Annoni, K. Howard, P. Seiler, and M. Guala, “An experimental investigation on the effect of individual turbine control on wind farm dynamics”, accepted to Wind Energy, 2015.

Other Significant Products:

1. D. Lim, S. Mantell, and P. Seiler, “Wireless Structural Health Monitoring of Wind Turbine Blades Using an Energy Harvester as a Sensor,” AIAA Atmospheric Flight Mechanics Conference, AIAA 2014-1395, 2014.
2. J. Annoni, J. Nichols, and P. Seiler, “Wind Farm Modeling and Control Using Dynamic Mode Decomposition,” AIAA Science and Technology Forum and Exposition, 2016.
3. J. Annoni, P. Seiler, K. Johnson, P. Fleming, and P. Gebraad, “Evaluating Wake Models for Wind Farm Control”, American Control Conference, p.2517-2523, 2014.
4. R. Louca, P. Seiler, and E. Bitar, “On Promoting Low Rank Solutions to Semidefinite Relaxations of Optimal Power Flow,” Allerton Conference on Communication, Control, and Computing, 2013.
5. P. Seiler, A. Pant, and J.K. Hedrick, ”Disturbance Propagation in Large Interconnected Systems,” *Proceedings of the American Control Conference*, pp. 1062-1067, 2002 (O. Hugo Schuck Award for best paper).

Synergistic Activities

2004-2008 Managed a joint project between the Honeywell Labs and the Air Transport business unit to develop the redundancy management architecture for the Boeing 787 flight control electronics.

2002- Consultant on the development of the "μ-Analysis and Synthesis Toolbox," and new "Robust Control Toolbox" software products distributed worldwide by The Mathworks for analysis and design of feedback systems in the presence of uncertainty.

Collaborators and Other Affiliations

Collaborators and Co-Editors: Eilyan Bitar (Cornell University), Jozsef Bokor (Hungarian Computer and Automation Research Institute), Joaquin Carrasco (Manchester) Sairaj Dhople (University of Minnesota), Demoz Gebre-Egziabher (University of Minnesota), Michele Guala (University of Minnesota), Vijay Gupta (Notre Dame) Sue Mantell (University of Minnesota), Andrew Packard (University of California, Berkeley), Tamas Peni (Hungarian Computer and Automation Research Institute), Jorge Sofrony (National University of Columbia), Fotis Sotiropoulos (SUNY-Stony Brook), Tim Smith (University of Minnesota), Ufuk Topcu (University of Texas, Austin), Balint Vanek (Hungarian Computer and Automation Research Institute), Elizabeth Wilson (University of Minnesota), Rusen Yang (University of Minnesota).

Graduate Advisors: Karl Hedrick (University of Califonia, Berkeley) and Raja Sengupta (University of California, Berkeley).

Postdoctoral Sponsor: Andrew Packard (University of California, Berkeley).

Graduate Advisees (8 Graduated Students): Andrei Dorobantu (Cymer), David Escobar Sanabria (U. of Minnesota), Paul Freeman (Northrup Grumman) Dongwong Lim (Korean AERI), Arda Ozdemir (Mathworks) Daniel Showers (Rockwell Collins), Will Thorson (Seagate) Timothy Wheeler (GMO Investing), Jen Annoni (Current), Abhineet Gupta (Current), Bin Hu (Current), Masanori Honda (Current), Sally Ann Keyes (Current), Aditya Kotikalpudi (Current), Adria Serra Moral (Current), Parul Singh (Current), Raghu Venkataraman (Current), Shu Wang (Current),

Postdoctoral Advisee (3 Total Scholars): Marcio Lacerda (Current), Harald Pfifer (Current), Daniel Ossmann (Current).

Biographical Sketch: SAIRAJ V. DHOPLE

(i) Professional Preparation

University of Illinois at Urbana-Champaign, Electrical Engineering, B.S., 2007
University of Illinois at Urbana-Champaign, Electrical Engineering, M.S., 2009
University of Illinois at Urbana-Champaign, Electrical Engineering, Ph.D., 2012

(ii) Appointments

Assistant Professor, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, January 2013-Present

(iii) Products – Five Most Closely Related to the Proposed Project

1. S. V. Dhople, B. B. Johnson, F. Dörfler, and A. O. Hamadeh,"Synchronization of Nonlinear Circuits in Generalized Dynamic Electrical Networks," to appear, *IEEE Transactions on Circuits and Systems-I: Regular Papers*, vol. 61, no. 9, pp. 2677–2690, Sept. 2014.
2. B. B. Johnson, S. V. Dhople, J. L. Cale, A. O. Hamadeh, and P. T. Krein, "Oscillator-Based Inverter Control for Islanded Three-Phase Microgrids ," *IEEE Journal of Photovoltaics*, vol. 4, no. 1, pp. 387–395, Jan. 2014. [Invited].
3. B. B. Johnson, S. V. Dhople, A. O. Hamadeh, and P. T. Krein, "Synchronization of Nonlinear Oscillators in Electrical LTI Networks," *IEEE Transactions on Circuits and Systems-I: Regular Papers*, vol. 61, no. 3, pp. 834–844, Mar. 2014.
4. B. B. Johnson, S. V. Dhople, A. O. Hamadeh, and P. T. Krein, "Synchronization of Parallel Single-Phase Inverters using Virtual Oscillator Control," *IEEE Transactions on Power Electronics*, vol. 29, no. 11, pp. 6124–6138, Nov. 2014.
5. S. V. Dhople, B. B. Johnson, and A. O. Hamadeh, "Virtual Oscillator Control for Voltage Source Inverters," in Proc. *51st Annual Allerton Conference on Communication, Control, and Computing*, 2013, pp.1359–1363 [Invited].

Five Other Significant Related Products

1. E. Dall'Anese, S. V. Dhople, and G. B. Giannakis, "Optimal Dispatch of Photovoltaic Inverters in Residential Distribution Systems," *IEEE Trans. on Sustainable Energy*, vol. 5, no. 2, pp. 487–497, Apr. 2014.
2. S. V. Dhople, J. L. Ehlmann, C. Murray, S. Cady, and P. L. Chapman, "Engineering Systems Deployed in the Gable House: A Passive, Net-Zero, Solar-Powered house for the U. S. Department of Energy's 2009 Solar Decathlon," in Proc. *IEEE Power and Energy Conference at Illinois*, 2010, pp. 58–62.
3. S. V. Dhople, Y. C. Chen, and A. D. Domínguez-García,"A Set-Theoretic Method for Parametric Uncertainty Analysis in Markov Reliability and Reward Models," *IEEE Transactions on Reliability*, vol. 62, no. 3, pp. 658–699, Sept. 2013.
4. R. K. Hester, C. Thornton, S. V. Dhople, Z. Zhao, N. Sridhar, and D. Freeman, "High-Efficiency Wide Load Range Buck/Boost/Bridge Photovoltaic Microconverter," in Proc. *IEEE Applied Power Electronics Conference*, 2011, pp. 309–313.
5. S. V. Dhople, J. L. Ehlmann, A. Davoudi, and P. L. Chapman, "Multiple-Input Boost Converter to Minimize Power Losses due to Partial Shading in Photovoltaic Modules," in Proc. *IEEE Energy Conversion Congress and Exposition*, 2010, pp. 2633–2636.

(iv) Synergistic Activities

- Reviewer for: *IEEE Transactions on Power Electronics*, *IEEE Transactions on Energy Conversion*, *IEEE Transactions on Power Systems*, *IEEE Transactions on Sustainable Energy*, *IEEE Journal of Photovoltaics*, *IEEE Transactions on Control Systems Technology*, *IEEE Transactions on Smart Grid*, *IEEE Transactions on Reliability*, *IET Renewable Power Generation.* Reviewer for: *IEEE Applied Power Electronics Conference* (2010, 2011, 2012, 2013), *IEEE Energy Conversion Congress and Exposition* (2010, 2011), *IEEE International Symposium on Circuits and Systems* (2009, 2011, 2012), *IEEE Innovative Smart Grid Technologies Conference* (2014)
- Conference service: Planning Committee, Minnesota Power Systems Conference (2013), Minneapolis, MN; Session chair, Climate and Weather Impacts: *North American Power Symposium* (2012), Urbana, IL; Session chair, Power Electronics: *IEEE Power and Energy Conference at Illinois* (2012), Urbana, IL; University relations chair: *IEEE Power and Energy Conference at Illinois* (2011), Urbana, IL; Session chair, Utility Interface Applications: *IEEE Applied Power Electronics Conference* (2010), Palm Springs, CA.
- Electrical engineering team leader, Solar Decathlon 2009: Led the University of Illinois at Urbana-Champaign (UIUC) Electrical Engineering team in the design of a sustainable, zero-energy home for the U.S. Department of Energy's 2009 Solar Decathlon competition. UIUC finished second among twenty university teams from around the world.
- Teaching: Green Electric Energy (University of Illinois at Urbana-Champaign, Fall 2011); Signals and Systems (University of Minnesota, Spring 2013); Power Systems Analysis (University of Minnesota, Fall 2013, Fall 2014).

(v) Collaborations & Other Affiliations

(a) Collaborators (US) F. Dörfler (ETH-Zürich), Brian Johnson (National Renewable Energy Laboratory), A. Hamadeh (Massachusetts Institute of Technology), P. L. Chapman (SolarBridge Technologies), R. K. Hester (Texas Instruments), D. Freeman (Texas Instruments), L. DeVille (University of Illinois at Urbana-Champaign), A. Davoudi (University of Texas at Arlington).

(b) Graduate Advisor: Alejandro D. Domínguez-García, University of Illinois at Urbana-Champaign

Christopher P Henze, Ph.D.

PERSONAL SUMMARY:

- 35 years of design experience specializing in power electronics for military, commercial and industrial applications
- 22 Patents and 28 technical publications in the field of power electronics

EXPERIENCE:

Consulting Electrical Engineer, Analog Power Design Inc., Lakeville, MN **1999 – Present**

Electrical Design Engineer, Vishay HiRel Systems, Minneapolis, MN **1999 – Present**

Design activities include, but not limited to:

- Design of a family of ac-ac converters for controlling fluorescent UV lamps for 3M manufacturing processes.
- Electrical design of 70kW and 130kW boost dc-dc converters for General Motors Fuel Cell power electrical vehicle.
- Design, build, test and evaluation of a 2.5kW bidirectional dc-dc converter for GM hybrid electric vehicle.
- Electrical design of inductively coupled battery chargers for underwater research applications.
- Design, build and test of a 350kW, 10kV capacitor charger for US Army Research Lab, for electromagnetic armor.
- Design of 40w/in3 dc-dc converter for Joint Strike Fighter.
- Design of ruggedized power supplies with single and three phase power factor correction, battery back up and charging, multiple input and outputs and high peak power capability for US Navy applications

General Manager, Lead Project Engineer

Densei USA, Burnsville, MN **1998-1999**

- Leader of a 12 person R&D team developing inductively coupled battery chargers for electrical vehicle applications.

Vice President of Engineering, Schott Power Systems, Wayzata, MN **1990-1999**

- Lead design engineer and team leader for multiple projects including 2000Adc output dc-dc converter for Cray Research and 25kW EV charging systems for General motors and 2kW shipboard power conditioners for US Navy.

Staff Electrical Engineering, Sperry DSD, Eagan, MN **1981-1999**

- Development of digital controller for power electronics, design of 50 w/in3 dc-dc converter for US Air Force.

EDUCATION:

Ph.D. Electrical Engineering (Minor Physics), 1986 --, University of Minnesota
M. S. Electrical Engineering (Minor Physics), 1983 --, University of Minnesota
B. S. Electrical Engineering , 1981 – Institute of technology, University of Minnesota

Biographical Sketch for Bradford Palmer

Director of Cummins PGBU Technology Development and Research
Cummins Global Product Line Architect for Power Electronics
1400 73rd Ave NE, Fridley, MN 55432, 763-574-5673, brad.k.palmer@cummins.com

Mr. Palmer is the Director of the Research and Technology Group for Cummins Power Generation (CPG) and the Global Product Line Architect for Power Electronics. He holds dual Engineering Masters Degrees from the University of Minnesota in electrical and mechanical engineering. His MSEE is in Power Electronics and Electro-Magnetic systems design. His MSME is in Engine Controls, and Propulsion Systems. He has worked in the area of power electronics and controls for over twenty years. He holds seven patents for brushless DC motor design, power electronics, and fuzzy tuned control methods.

He has been employed by Cummins Power Generation (CPG) for fifteen years, and in that time has worked on a variety of projects and in a number of roles; including the manager of the CPG advanced electronics group, technical project leader for hybrid electric vehicle (HEV) systems, and as the technical lead for power electronics and controls for Cummins Power Generation's fuel cell research (SECA) program. He is currently the Director of the Research and Technology Group for Cummins Power Generation (CPG) and the Global Product Line Architect for Power Electronics.

Professional Preparation

2005 M.S. in Electrical Engineering, University of Minnesota, Minneapolis, MN
2000 M.S. in Mechanical Engineering, University of Minnesota, Minneapolis, MN
1990 B.S. in Mechanical Engineering, University of Minnesota, Minneapolis, MN

Appointments

Director, 2014 - present
Director of Cummins PGBU Technology Development and Research
Cummins Global Product Line Architect for Power Electronics

Manager Advanced Electronics Development, 2010 - 2014
Cummins Power Generation Advanced Engineering Group

Technical Project Lead Hybrid Systems, 2007 - 2010
Cummins Power Generation

Technical Project Lead, Controls/Power Electronics SECA SOFC Project, 2003 - 2007
Cummins Power Generation

Power Electronics and Controls Engineer, 2001 - 2003
Cummins Power Generation

Power Electronics and Controls Engineer, 1996 - 2001
Horton Inc.

Products Most Related to Proposed Project

- Patent Number 6,912,353, Brushless DC ring motor cooling system
- Patent Number 6,600,249, Brushless DC ring motor cooling system
- Patent Number 6,548,929, Eddy current fan drive

- Patent Number 6,253,716, Control system for cooling fan assembly having variable pitch blades
- Patent Number 6,109,871, Integrated fan assembly with variable pitch blades
- Patent Number 8,912,672, Control of an engine-driven generator to address transients of an electrical power grid connected thereto
- Patent Number 8,623,533, High temperature fuel cell system with an electrical heater
- Patents Pending 20150207396, Split Phase Power Conversion Apparatuses, Methods and Systems
- Patents Pending 20150076820, CONTROL OF AN ENGINE-DRIVEN GENERATOR TO ADDRESS TRANSIENTS OF AN ELECTRICAL POWER GRID CONNECTED THERETO
- Patents Pending 20140156099, GENERATOR POWER SYSTEMS WITH ACTIVE AND PASSIVE RECTIFIERS

Synergistic Activities

- Dakshina Murthy-Bellur, Elias Ayana, Sergey Kunin and Brad Palmer, "High-Frequency Split-Phase Air-Cooled SiC Inverter for Vehicular Power Generators" Cummins Power Generation, USA. 2015 IEEE Transportation Electrification Conference and Expo

Dakshina Murthy-Bellur

Technical Specialist – Electrical Engineer
Advanced Engineering
Cummins Power Generation

1400 73rd Avenue NE
Minneapolis, MN 55432

Phone: (763) 574-3448
dakshina.murthy-bellur@cummins.com

EDUCATION

Ph.D., Engineering (2010) and M.S., Electrical Engineering (2006)
Wright State University, Dayton, OH, USA. Advisor: Prof. Marian K. Kazimierczuk

B.E., Electrical and Electronics Engineering (2003)
Dayananda Sagar College of Engineering, Bangalore, Karnataka, India
Affiliated to Visvesvaraya Technological University, Belgaum, Karnataka, India

PROFESSIONAL EXPERIENCE

Technical Specialist – Electrical Engineer, Advanced Engineering,
Cummins Power Generation, Minneapolis, MN — Oct. 2012 – present

Technology Development Role: *Develop power electronics through creation of technology platforms for power generation and vehicle electrification applications. Apply industry standard processes to transform research concepts in to commercial products which are manufacturable, reliable, and safe.*

- As a lead engineer, developed a 3-16kW modular/scalable Si & SiC inverter platform
- Currently leading the development of 3-15kW modular/scalable isolated DC-DC converter platform
- Supporting the development of electric accessory drives for on- and off-highway vehicles

Research Role: *Conduct research related to electric energy systems to develop new technology roadmaps in power electronics for Cummins Inc. specifically aimed at power generation, vehicle electrification, micro-grids, and renewables integration*

- Served as an industry advisor for the DOE-Purdue-Cummins sponsored power electronics exploratory research investigating DC-DC converters for vehicle charging applications at Purdue's Hoosier Heavy Hybrid Centre of Excellence

Assistant Professor of Electrical and Computer Engineering
School of Engineering, Penn State Behrend, Erie, PA — Aug. 2010 – July 2012

Teaching: Courses taught - Power Electronics, Electromechanical Energy Conversion, Linear Control Systems, Signals and Controls Laboratory, Circuits and Devices Laboratory, and Digital System Design Laboratory

- Supervised 10 undergraduate research students and 4 senior capstone projects

Research: Conducted research and advised undergraduate students in several projects related power electronics.

- Studied the effect of harmonics on winding power losses in magnetic devices used in high-frequency pulse-width modulated DC-DC power converters
- Designed and developed loosely coupled inductors for wireless power transfer applications
- Conducted pedagogical research related to the theory of LC sinusoidal oscillators
- Developed and delivered $13k internally sponsored undergraduate research

Service: Chair - Ad Hoc Energy, Motors, and Controls Laboratory Curriculum Committee, Member - Ad Hoc Energy and Sustainability Curriculum Committee, Member - Research and Outreach Centers Committee, Member - Consortium of Universities for Sustainable Power (CUSP)

Graduate Teaching and Research Assistant
Department of Electrical Engineering, Wright State University, Dayton, OH — Sept. 2006 – June 2010

- Developed five novel PWM DC-DC converter circuits for low power applications
- Devised methodologies to design high-frequency inductors and transformers for power converter applications
- Developed new hardware and software lab curriculum for advanced graduate courses in power electronics
- Conducted lab sessions, taught theories and concepts of electric circuits, control systems, and power electronics for graduate and undergraduate students for a total of 13 quarters

Summer Intern, Controls Engineering,
Cummins Power Generation, Minneapolis, MN — June – Sept. 2008

- Designed a 3kW bidirectional DC-DC converter for an alternative power supply application
- Developed and tested the DC-DC converter up to 1kW using a newly designed planar transformer

SELECTED PUBLICATIONS

CONTRIBUTION TO TEXT BOOK

Contributed towards development of two chapters (10 & 11) related to the design of high-frequency inductors and transformers in the following text book:
M. K. Kazimierczuk, *High-Frequency Magnetic Components*, 2nd Ed., John Wiley & Sons, New York, NY, 2014, pp.1-725, ISBN-978-1-118-71779-0. (The monograph/textbook is intended for graduate students, researchers, and practicing engineers)

CONFERENCE PAPERS

C1 **D. Murthy-Bellur**, E. Ayana, S. Kunin, and B. Palmer, "High-Frequency Split-Phase Air-Cooled SiC Inverter for Vehicular Power Generators," *2015 IEEE Transportation Electrification Conference and Expo*, Detroit, MI, June 14 - 17, 2015, pp. 01 – 05.

C2 **D. Murthy-Bellur**, E. Ayana, S. Kunin, B. Palmer, and S. Varigonda "WBG Inverter for Commercial Power Generation and Vehicle Electrification," *2015 IEEE International Workshop on Integrated Power Packaging*, Chicago, IL, May 03 - 06, 2015, pp. 36 - 39.

C3 M. Cai, L. Wu, **D. Murthy-Bellur**, M. Saeedifard, and O. Wasynczuk, "Influence of Si & SiC Device Selection on Losses and Magnetics Design in an Isolated DC-DC Converter," *2015 IEEE International Workshop on Integrated Power Packaging*, Chicago, IL, May 03 - 06, 2015, pp. 68 - 71.

C4 **D. Murthy-Bellur**, A. Bauer, W. Kerin, and M. K. Kazimierczuk, "Inverter Using Loosely Coupled Inductors for Wireless Power Transfer," *IEEE International Midwest Symposium on Circuits and Systems*, Boise, ID, Aug. 5 - 8, 2012, pp. 1164 - 1167.

C5 **D. Murthy-Bellur** and M. K. Kazimierczuk, "Active-Clamp ZVS Two-Switch Flyback Converter," *IEEE International Symposium on Circuits and Systems*, Rio de Janeiro, Brazil, May 15 - 18, 2011, pp. 241 - 244.

C6 **D. Murthy-Bellur** and M. K. Kazimierczuk, "Two-Switch Flyback-Forward PWM DC-DC Converter with Reduced Switch Voltage Stress," *IEEE International Symposium on Circuits and Systems*, Paris, France, May 30 - June 2, 2010, pp. 3705 - 3708.

C7 **D. M. Bellur** and M. K. Kazimierczuk, "PSpice and MATLAB Applications in Teaching Power Electronics to Graduate Students at Wright State University," *2008 ASEE North Central Section Conference*, Dayton, OH, March 28 - 29, 2008.

C8 **D. M. Bellur** and M. K. Kazimierczuk, "DC-DC Converters for Electric Vehicle Applications," *Proceedings of Electrical Insulation Conference and Electrical Manufacturing Expo*, Nashville, TN, October 22 - 24, 2007, pp. 286 - 293.

JOURNAL ARTICLES

J1 **D. Murthy-Bellur**, S. Kunin, E. Ayana, B. Palmer, J. Leonarski, S. Varigonda, and K. Shenai, "Design and Performance of Compact Air-Cooled SiC MOSFET Inverters for Low-Power Variable-Speed Drive Applications," *Transactions on Electrochemical Society*, vol. 64, no. 7, pp. 61 – 75, 2014.

J2 **D. Murthy-Bellur** and M. K. Kazimierczuk, "Zero-Current Transition Two-Switch Flyback Pulse-Width Modulated DC-DC Converter," *IET Power Electronics*, vol. 4, no. 3, pp. 288 - 295, Mar. 2011.

J3 **D. Murthy-Bellur** and M. K. Kazimierczuk, "Isolated Two-Transistor Zeta Converter with Reduced Transistor Voltage Stress," *IEEE Transactions on Circuits and Systems - II, Express Briefs*, vol. 58, no. 1, pp. 41 - 45, Jan. 2011.

J4 **D. Murthy-Bellur** and M. K. Kazimierczuk, "Winding Losses caused by Harmonics in High Frequency Flyback Transformers for Pulse-Width Modulated DC-DC Converters in Discontinuous Conduction Mode," *IET Power Electronics*, vol. 3, no. 5, pp. 804 - 817, Sept. 2010.

J5 **D. Murthy-Bellur** and M. K. Kazimierczuk, "Two-Transistor Zeta-Flyback DC-DC Converter with Reduced Transistor Voltage Stress," *Electronics Letters*, vol. 46, no. 10, pp. 719 - 720, May 2010.

PROFESSIONAL SERVICE

- **Technical Committee Member** – IEEE IWIPP Chicago, IL, 3-6 May 2015; EISTCON 2012, Bangalore, India, 3-4 May 2012. **Session Chair** – IEEE ITEC 2015, Detroit, MI, 14-17 June 2015; ASEE NCS, Dayton, OH, 28-29 Mar. 2008
- **Active Technical Reviewer** for: IEEE Trans. on Ind. Electronics, IEEE Trans. on Power Electronics, IET Power Electronics, IET Circuits, Devices & Systems, IEEE International Symposium on Circuits and Systems (ISCAS 2006, 2010), IEEE ECCE (2011, 2012), International Journal of Circuit Theory and Applications, ASEE NCS 2008, 2011
- **Professional Member** of SAE, IEEE, IEEE Circuits and Systems Society (CAS), Electrical, Manufacturing and Coil winding Association (EMCWA), 2005 – present
- **STEM-based outreach:** Presenter/coordinator for Penn State Behrend's MATH OPTIONS program, May 10, 2011; Wright State University's Science, Technology, and Engineering Preparatory Program (Wright STEPP) June – July, 2006 and 2009.

Daniel F. Opila

Professional Preparation

Massachusetts Institute of Technology , Mechanical Engineering, B.S., 2002
Massachusetts Institute of Technology , Mechanical Engineering, M.S., 2003
University of Michigan, Mechanical Engineering, Ph.D., 2010
University of Michigan, Electrical Engineering (Power Systems), Postdoctoral, 2011

Appointments

2014-present	Assistant Professor, United States Naval Academy
2010-2014	Senior R&D Engineer, General Electric Power Conversion
2008-2010	Visiting Scholar, Ford Motor Company
2005-2006	Senior Engineer, Orbital Sciences Corp.
2003-2005	Research and Development Engineer, Bose Corp.

Five Most Closely Related Publications

L. Solomon, A. Permuy, N.D. Benavides, D.F. Opila, C.F. Lee, and G.F Reed. “Modular Multilevel Medium Voltage Converters Based on Printed Circuit Boards,” *IEEE Transactions on Power Electronics*. vol: PP, no. 99.

K. Lentijo, D.F. Opila, “Minimizing Inverter Self-synchronization due to Reactive Power Injection on Weak Grids,” *2015 IEEE Energy Conversion Congress and Exposition*, Montreal, Canada, September 2015.

D. Opila, M. Zeynu, and I. Hiskens, "Wind farm reactive support and voltage control" *International Institute for Research and Education in Power Systems (IREP) VIII Bulk Power System Dynamics and Control*, Buzios, Brazil, August 2010.

H. Park, J. Sun, S. Pekarek, R. DeCarlo, P. Stone, and D. Opila. “Real-time Model Predictive Control for Shipboard Power Management Using the IPA-SQP Approach,” *IEEE Transactions on Control Systems Technology*, vol: PP, no. 99.

D. Opila and L. Solomon, “Optimal control of dynamic pulse power loads in naval power systems using the Pontryagin minimum principle and Dynamic Programming,” *IEEE Power and Energy Society General Meeting*, San Diego, CA, July 2012.

Five Other Significant Publications

D. Opila, X. Wang, R. McGee, R. Gillespie, J. Cook, and J. Grizzle, “Real-World Robustness for Hybrid Vehicle Optimal Energy Management Strategies Incorporating Drivability Metrics,” *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 136, no. 6, August 2014. DOI: 10.1115/1.4027680

D. Opila, X. Wang, R. McGee, and J. Grizzle, “Real-Time Implementation and Hardware Testing of a Hybrid Vehicle Energy Management Controller Based on Stochastic Dynamic Programming.” *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 135, no. 2, March 2013.

D. Opila, X. Wang, R. McGee, R. Gillespie, J. Cook, and J. Grizzle, “An Energy Management Controller to Optimally Tradeoff Fuel Economy and Drivability for Hybrid Vehicles.” *IEEE Transactions on Control Systems Technology*, vol. 20, no. 6, November 2012.

D. Opila, D. Aswani, R. McGee, J. Cook, and J. Grizzle, “Incorporating drivability metrics into optimal energy management strategies for hybrid vehicles,” *in Proceedings of 2008 IEEE Conference on Decision and Control*, Cancun, Mexico, December 2008.

D. Opila, A. Annaswamy, W. Krol, S. Raghu. “Biomimetic reduction of wake deficit using tail articulation at low reynolds number*.” IEEE Journal of Oceanic Engineering*, vol. 29, no. 3, July 2004.

Synergistic Activities

Reviewer:

- IEEE Transactions on Vehicular Technology
- IEEE Transactions on Control Systems Technology
- Applied Energy
- Simulation Modelling Practice and Theory
- Meccanica
- American Control Conference
- European Control Conference
- ASME Dynamic Systems and Control Conference
- IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling

Member:

- ASME-American Society of Mechanical Engineers,
- IEEE- Institute of Electrical and Electronics Engineers

Graduate and Postdoctoral Advisors

Jessy Grizzle and Brent Gillespie, University of Michigan
Ian Hiskens, University of Michigan

Collaborators

Xiaoyong Wang, Ford Motor Company
Ryan McGee, Ford Motor Company
Brent Gillespie, University of Michigan
Jeff Cook, University of Michigan
Jessy Grizzle, University of Michigan
Honjeon. Park, University of Michigan
Jing Sun, University of Michigan
Steve Pekarek, Purdue University
Ray DeCarlo, Purdue University
Philip Stone, General Electric
Luke Solomon, General Electric
Alfred Permuy, General Electric
Christopher Lee, General Electric
Gregory Reed, University of Pittsburgh

Total number of graduate students advised: 0
Total number of postdoctoral scholars sponsored: 0