Final Scientific/Technical Report

Northeastern University

Final Scientific/Technical Report

A Universal Converter for DC, Single-phase AC, and Multi-phase AC Systems

DE-AR0000902

Award:	DE-AR0000902
Lead Recipient:	Northeastern University
Project Title:	A Universal Converter for DC, Single-phase AC, and Multi-phase AC Systems
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Public Executive Summary

The goal of this project was to develop a new class of universal power converters that utilize the unique properties of WBG switches, including high reverse voltage blocking and fast switching, to achieve superior performance in universal converters. Some of the features of the proposed converter are as follows:

1) Significantly longer lifetime, higher power density, lower costs associated with bill of materials, and lower shipping, installation, and repair costs compared to the existing WBG-based solutions,

2) Very flexible operation for transferring power between any type of source (dc, single-phase ac, or multi-phase ac) and any type of load (dc, single-phase ac, or multi-phase ac) without using large passive components or additional stages/components, even when the instantaneous values of input and output power are not the same, and

3) High performance operation at all power levels.

Considering its advantages and wide range of applications, the proposed converter has the potential to create a new paradigm in power electronics. Among numerous applications of this converter are electric vehicles, wind energy systems, PV systems, industrial motor drives, residential variable frequency drive systems, and nanogrid applications. This project focused on the application of this converter for residential PV, residential motor drive, and industrial motor drive applications, and evaluated the performance of this converter for these applications.

Acknowledgements

We would like to thank ARPA-E for supporting this project. In particular, we thank the program director, Dr. Isik Kizilyalli, as well as Dr. Ziaur Rahman and Dr. Daniel Cunningham, for guiding the team throughout the execution of the project. We would also like to thank MassCEC for providing the cost share of this project.

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Accomplishments and Objectives

This award allowed Northeastern University to develop a new universal power converter topology and evaluate it for different applications. Some of the features of this converter are as follows:

1) Significantly longer lifetime, higher power density, lower costs associated with bill of materials, and lower shipping, installation, and repair costs compared to the existing WBG-based solutions,

2) Very flexible operation for transferring power between any type of source (dc, single-phase ac, or multi-phase ac) and any type of load (dc, single-phase ac, or multi-phase ac) without using large passive components or additional stages/components, even when the instantaneous values of input and output power are not the same, and

3) High performance operation at all power levels.

The focus of the project was on three applications:

- Residential motor drive (single-phase ac to three-phase ac converter)
- Residential PV inverter (single-phase inverter)
- Industrial motor drive (three-phase ac to three-phase ac converter)

Several tasks and milestones were laid at the beginning of the project. However, some of these tasks were affected by the pandemic, as the team faced lack of personnel during pandemic. The actual performance against the stated milestones is summarized in Table 1.

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: Design and Fabrication of a 10 kW universal prototype 1.1 Optimizing filter components for each application and fabricating the boards 1.2 Designing SiC gate driver for all applications. 1.3 Design PCB layout	M1: Simulating the gate driver circuit (switch voltage=1200 V and switch current= 40 A). Present to ARPA-E Program Director for acceptance of completed simulation performance of the gate driver meeting the followings: • 28 V/ns <dv/dt <50 V/ns • 0.7<di/dt<1 A/ns • Overshoot of Vds<1.3*Vdc Actual Performance: (Completion date: 3/20/2018) This milestone was fully met, and the performance of the designed and simulated gate driver is as follows: Turn-off dv/dt= 45.45 V/ns Turn-off di/dt= 0.98 A/ns Turn-on dv/dt= 48 V/ns Turn-on di/dt= 0.95 A/ns Overshoot< 1.05*vdc M2: Testing the gate driver with a basic circuit (switch voltage=500 V and switch current= 20 A). Present to ARPA-E Program Director for acceptance of completed and demonstrated the performance of the gate driver met the followings: • 28 V/ns <dv/dt <50 V/ns

Tasks	Milestones and Deliverables
	• 0.7<di/dt<1 A/ns • Overshoot of Vds<1.3*Vdc (considering the equipment limitation, the gate driver will be tested @ 500 V and 20 A; however, we will use the simulation results to validate the performance of the gate driver @1200 V and 40 A) Actual Performance: (Completion date:6/20/2018) This milestone was fully met, and the performance of the designed and tested gate driver is as follows: Turn-off dv/dt= 30.21 V/ns Turn-off di/dt= 0.763 A/ns Turn-on dv/dt= 25.15 V/ns Turn-on di/dt= 0.929 A/ns Overshoot= 1.3*vdc M3: Meeting the weight target. CAD model estimation for weight of the prototype (excluding the sensors)< 2 kg Actual Performance: (Completion date: 6/20/2018) This milestone was fully met. The estimated weight of the inductor cores and capacitors for each application is as follows: Single- phase ac to three-phase ac converter: 1.7 kg Single-module PV inverter: 0.378kg Three-module PV inverter: 0.991 kg Hybrid PV/Battery inverter: 1.945 kg Three-phase ac-ac converter: 1.99 kg
Task 2: Validation for single-phase ac to three-phase ac motor drive for residential applications (2.5 kW) 2.1 Simulating the single-phase ac to three-phase ac converter (2.5 kW) when ideal source and RL load are used 2.2 Testing the prototype for a 1ϕ ac⇔3ϕ ac system using ideal sources and loads 2.3 Simulating the 1 ϕ ac⇔ 3 ϕ ac converter when an	M1: Validate performance of the single-phase ac to three-phase ac converter (2.5 kW) through simulation when ideal sources/ and RL load are used. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 2.5 kW (excluding the power loss of the input and output filters) > 97% • THD of currents @ 2.5 kW <5% Actual Performance: (Completion date:9/20/2018) This milestone was met, and performance of the simulated converter was evaluated: • Efficiency @ 2.5 kW= 97.9% • THD of input currents @ 2.5 kW =0.9% • THD of output currents @ 2.5 kW =0.6% M2: Validate performance with ideal sources/ and RL load. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 2.5 kW (excluding the power loss of the input and

Tasks	Milestones and Deliverables
induction motor is used as the load 2.4 Simulating the 1 ϕ ac⇔ 3 ϕ ac converter using an induction motor as the load and implementing V/Hz controller 2.5 Testing the prototype for a 1 ϕ ac⇔ 3 ϕ ac system using an induction motor 2.6 Design and implement V/Hz controller	output filters) for 10 minutes of running >97% • THD of currents<5% • Validate EMC Compliance using a LISN (Line Impedance Stabilizer Network) and a spectrum analyzer Actual Performance: (Completion date:12/20/2018) This milestone was mostly met. The performance of the converter was experimentally evaluated: • Efficiency= 95.7% • Input Current THD = 2.3% (target <5%) • Output Current THD = 3.5% (target <5%) • EMI noise<79dBuV M3: Validate performance of the 1 ϕ ac⇔ 3 ϕ ac converter through simulation when V/Hz control is applied and an induction motor is used as the load. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 2.5 kW (excluding the power loss of the input and output filters) for 10 minutes of running >97% • THD of currents<5% @ 2.5 kW. • Demonstrate V/Hz control Actual Performance: (Completion date: 3/20/2019) This milestone was met, and the performance of the converter when an induction motor is used as a load was evaluated through simulations: • Input Current THD = 2.5% • Output Current THD = 3.5% • The efficiency of the converter without any snubber= 97.2% The efficiency of the converter with large snubbers= 94.9% • V/Hz Control was evaluated through simulations M4: Validate performance and V/Hz control when using an induction motor. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 2.5 kW (excluding the power loss of the input and output filters) for 10 minutes of running >97% • THD of currents<5% @ 2.5 kW • Demonstrate V/Hz control Actual Performance: (Completion date:6/20/2019) This milestone was mostly met. The converter was experimentally tested when an induction motor was used as a load, and the V/Hz

Tasks	Milestones and Deliverables
	control was validated. The performance of the converter was evaluated: • Tested the converter with an induction motor • V/Hz Control was evaluated through experiment • Input Current THD = 2.6% • Output Current THD = 4.5% • The efficiency of the converter with large snubbers= 92.35% (given the slow dynamic of the motor and to avoid high voltage spikes large snubbers are used. We have shown that by using 3.3 kV SiC MOSFETs the efficiency will be 97.12%)
Task 3: Verification for micro-inverter (one PV module: 330 W) 3.1 Simulating the dc => 1ϕ ac inverter using ideal source and load 3.2 *Testing the prototype for a* dc => 1ϕ ac *system using ideal source and load* 3.3 Simulating the grid-connected dc => 1ϕ ac inverter when PV modules are used as the source 3.4 Implement MPPT feature in simulation 3.5 Design and implement closed loop controllers for reactive power and active power grid support in simulation 3.6 *Testing the prototype for a* dc => 1ϕ ac *system using a PV simulator and a grid simulator* 3.7 *Implement MPPT feature*	M1: Validate performance of the dc => 1ϕ ac inverter through simulation when ideal source and RL load are used. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 330 W (excluding the power loss of the input and output filters) >95% • THD of output currents<5% @ 330W • DC current ripple <5% of input current @ 330W Actual Performance: (Completion date:9/20/2018) This milestone was met, and the performance of the simulated converter was evaluated: • Efficiency @ 330 W = 96.2% • THD of output currents=1.09% @ 330W • DC current ripple =2.93% of input current @ 330W M2: Validate performance with ideal source and RL load. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 330 W (excluding the power loss of the input and output filters) for 10 minutes of running >95% • THD of output currents<5% @ 330W • DC current ripple <5% of input current @ 330W • Validate EMC Compliance using a LISN (Line Impedance Stabilizer Network) and a spectrum analyzer Actual Performance: (Completion date:12/20/2018) This milestone was met. The fabricated inverter was tested, and the following results were achieved: • Efficiency=94.35% • THD of output current=3.62%

Tasks	Milestones and Deliverables
3.8 *Design and implement closed loop controllers for reactive power and active power grid support*	• DC current ripple=2.4% M3: Validate performance of the dc => 1ϕ ac inverter through simulation when MPPT and active and reactive power control are implemented. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 330 W (excluding the power loss of the input and output filters) >95% • Validate unity power factor control on a <70% lagging load • Validate MPPT (difference between measured PV power and Maximum PV power<5%) • Steady state error of active and reactive power<2% Actual Performance: (Completion date:3/20/2019) This milestone was met. The following results were achieved: • Efficiency=96% (unfiltered) • THD of output current=3.2% • MPP error =Maximum PV power-Measured PV power=1.8e-4 (<5%) • P_Error=1.57% • Q_Error=2.27% M4: Validate MPPT and active and reactive power control with grid simulator and PV simulator/PV panels. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 330 W (excluding the power loss of the input and output filters) for 10 minutes of running >95% • Validate unity power factor control on a <70% lagging load • Validate MPPT (difference between measured PV power and Maximum PV power<5%) • Steady state error of active and reactive power<2% Actual Performance: (Completion date:6/20/2019) This milestone was mostly met. • MPPT algorithm was verified by experiment, using PV simulator as input and grid simulator as output • PF=1 and PF=0.7 (both leading and lagging) cases were tested • The efficiency including filter losses was 90.45%. By removing link capacitor voltage sensors, reducing switching frequency to 25 kHz, and excluding filter losses the efficiency can be increased to 95.9%.

Tasks	Milestones and Deliverables
	• MPPT accuracy =95.68% • Steady state error of active and reactive power 1.95% and -1.92%, respectively <2%
Task 4: Validation for wind energy system (10 kW) 4.1 Simulating the 3ϕ ac⇔3ϕ ac converter using ideal source and RL load 4.2 Testing the prototype for a 3ϕ ac⇔3ϕ ac system using ideal source and RL load 4.3 Simulating the grid-connected 3ϕ ac⇔3ϕ ac converter 4.4 Testing the prototype for a 3ϕ ac⇔3ϕ ac system using a grid simulator 4.5 Design and implement closed loop controllers for reactive power and active power grid support in simulation 4.6 Implement features including High/Low Voltage Ride-Through (H/LVRT) High/Low Frequency Ride-Through (H/LFRT), and emergency	M1: Validate performance of the 3ϕ ac⇔3ϕ ac converter through simulation when ideal source and RL load are used. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 10 kW (excluding the power loss of the input and output filters) >97% • Efficiency @ 500 W (excluding the power loss of the input and output filters) >98% • THD of output currents<5% @ 10kW. Actual Performance: (Completion date:9/20/2019) This milestone was fully met. Initially the team worked on wind application and with the selected system parameters 3300 V switches were required, and the team did not have access to these switches. After discussing this problem with the program manager, the application was changed, and this milestone was modified. For wind application, the team simulated both soft-switching and hard-switching configurations @ full power, 50% load, and 25% load: • Efficiency of hard-switching topology @ full power using 1.7 kV SiC MOSFETs= 96% • THD of the output currents=1.3% The application was changed to industrial motor drive instead of wind power generation system (the parameters of the system was modified to make sure 1700 V switches can be used). The converter was simulated for the new application with the ideal sources and loads, and efficiency and THD were measured: • Full power: η=94% , Input Current THD ~3.4%, Output Current THD ~3.1%, • 25% load: η=97.4% • 5% load:η=97.1% (soft-switching) • Developed a modified topology with a new control scheme to improve the efficiency • Full power: η=97%

Tasks	Milestones and Deliverables
shutdown/disconnects in simulation 4.7 Design and implement closed loop controllers for reactive power and active power grid support 4.8 Implement features including High/Low Voltage Ride-Through (H/LVRT) High/Low Frequency Ride-Through (H/LFRT), and emergency shutdown/disconnects.	M2: Validate performance with ideal source and RL load. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 10 kW (excluding the power loss of the input and output filters) for 10 minutes of running >97% • Efficiency @ 500 W (excluding the power loss of the input and output filters) for 10 minutes of running >98% • THD of output currents<5% @ 10kW. • Validate EMC Compliance using a LISN (Line Impedance Stabilizer Network) and a spectrum analyzer Actual Performance: (Completion date: N/A) This milestone was partially met. The team tested the converter up 2 kW at 40 kHz. Due to lack of personnel and budget, which was imposed by the pandemic, the milestone was not met. M3: Validate performance of the grid-connected 3ϕ ac⇔3ϕ ac converter through simulation. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 10 kW (excluding the power loss of the input and output filters) >97% • Efficiency @ 500 W (excluding the power loss of the input and output filters) >98% • THD of output currents<5% @ 10 kW. • Validate bidirectional operation through simulation Actual Performance: (Completion date: N/A) This milestone was not met due to change of application. M4: Validate performance with grid simulator. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 10 kW (excluding the power loss of the input and output filters) for 10 minutes of running >97% • Efficiency @ 500 W (excluding the power loss of the input and output filters) for 10 minutes of running >98% • THD of output currents<5% @ 10 kW • Validate bidirectional operation through simulation

Tasks	Milestones and Deliverables
	Actual Performance: (Completion date: N/A) This milestone was not met due to change of application. M5: Validate performance of the grid-connected 3ϕ ac⇔3ϕ ac converter through simulation when active and reactive power control, H/LVRT, H/LFRT, and emergency shutdown/disconnects are implemented. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • THD of output currents<5% @ 10 kW • Steady state error of active and reactive power<2% • Validate H/LVRT, H/LFRT, and emergency shutdown/disconnects Actual Performance: (Completion date:9/1/20) This milestone was modified since the application changed. The team implemented vector control for the motor drive system and the results are as follows: • Implemented vector control and verified the performance of system at 100%, 50%, and 25% load • Efficiency at full power: 94.35% • Input current THD at full power: 1.9% • Output current THD at full power: 1.6% • Steady state error of motor speed =0.12% M6: Validate active and reactive power control, H/LVRT, H/LFRT, and emergency shutdown/disconnects. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • THD of output currents<5% @ 10kW. • Steady state error of active and reactive power<2% • Validate H/LVRT, H/LFRT, and emergency shutdown/disconnects Actual Performance: (Completion date: N/A) This milestone was not met due to change of application and lack of personnel.

Tasks	Milestones and Deliverables
Task 5: Validation for multi-module micro-inverter (three PV modules:1 kW) and microgrid systems formed a DC source, PV panels, and ac load (6 kW) 5.1 Simulating the grid-connected (dc + dc +dc)=> 1ϕ ac converter 5.2 Testing the prototype for a (dc + dc +dc)=> 1ϕ ac system using PV simulators and grid simulator 5.3 Simulating the (dc +dc) => 1ϕ ac inverter using ideal sources and load 5.4 Testing the prototype for a (dc +dc) => 1ϕ ac system using ideal sources and load 5.5 Simulating the grid-connected (dc +dc) => 1ϕ ac inverter 5.6 Design and implement closed loop controllers for reactive power and active power grid support in simulation 5.7 Testing the prototype for (dc +dc) => 1ϕ ac system using PV panels and grid simulator 5.8 Design and implement closed loop controllers for reactive power and active power grid support	M1: Validate performance of the (dc + dc +dc)=> 1ϕ ac inverter through simulation when PV modules are used as the sources and grid is used as the load. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 1 kW (excluding the power loss of the input and output filters) >95% • THD of output current<5% • DC current ripple for all the inputs<5% of input current Actual Performance: (Completion date:9/20/2019) This milestone was met. The multi-module inverter was simulated using accurate model of switches. The following results were achieved: • Efficiency=96.5% • THD of output current= 3.3% • DC current ripple for all the inputs=2.5% M2: Validate performance with grid simulator and PV simulator/PV panels. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 1 kW (excluding the power loss of the input and output filters) for 10 minutes of running >95% • THD of output current<5% • DC current ripple for all the inputs<5% of input current • Validate EMC Compliance using a LISN (Line Impedance Stabilizer Network) and a spectrum analyzer Actual Performance: (Completion date) Due to lack of personnel and budget, which was imposed by the pandemic, the milestone was not met. M3: Validate the performance of the (dc +dc) => 1ϕ ac inverter when ideal sources/loads are used. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 6 kW (excluding the power loss of the input and output filters) >97% • Efficiency @ 300 W (excluding the power loss of the input and output filters) >99% • THD of output currents<5% @ 6kW.

Tasks	Milestones and Deliverables
	• DC current ripple<5% of input current @ 6kW. Actual Performance: (Completion date: 3/20/2020) This milestone was mostly met. The multi-port inverter was simulated @ 6 kW, and the following results were achieved: • Measured efficiency and THD @ 6 kW • THD=2.67% • Efficiency=97.1% M4: Validate performance with ideal sources/loads. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Efficiency @ 6 kW (excluding the power loss of the input and output filters) for 10 minutes of running >97% • Efficiency @ 300 W (excluding the power loss of the input and output filters) for 10 minutes of running >99% • THD of output currents<5% @ 6kW. • DC current ripple<5% of input current @ 6kW. • Validate EMC Compliance using a LISN (Line Impedance Stabilizer Network) and a spectrum analyzer Actual Performance: (Completion date: N/A) Due to lack of personnel and budget, which was imposed by the pandemic, the milestone was not met. M5: Validate performance of the (dc +dc) => 1ϕ ac inverter through simulation when active/reactive power control is implemented. Present to ARPA-E Program Director for acceptance of completed simulation performance of the converter meeting the followings: • Efficiency @ 6 kW (excluding the power loss of the input and output filters) >97% • Efficiency @ 300 W (excluding the power loss of the input and output filters) >99% • THD of output currents<5% • Steady state error of active and reactive power<2% Actual Performance: (Completion date:N/A) Due to lack of personnel and budget, which was imposed by the pandemic, the milestone was not met. M6: Validate performance and active and reactive control with grid simulator and PV simulator/PV panels. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the

Tasks	Milestones and Deliverables
	followings: • Efficiency @ 6 kW (excluding the power loss of the input and output filters) for 10 minutes of running >97% • Efficiency @ 300 W (excluding the power loss of the input and output filters) for 10 minutes of running >99% • THD of output currents<5% • Steady state error of active and reactive power<2% Actual Performance: (Completion date: N/A) Due to lack of personnel and budget, which was imposed by the pandemic, the milestone was not met.
Task 6: EM Compliance Test & continuous basic operation	M1: Validate EM Compliance & continuous basic operation. Present to ARPA-E Program Director for acceptance of completed and demonstrated test met the followings: • Demonstrate 168-hours continuous operation for selected applications • Verify EM compliance according to FCC Part 15 • Power density for 10 kW system: o Non-isolated: 13.4 kW/L, Isolated: 11.5 kW/L • Specific power for 10 kW system: o Non-isolated: 14.3 kW/kg, Isolated: 5.7 kW/kg Actual Performance: (Completion date: N/A) Due to lack of personnel and budget, which was imposed by the pandemic, the milestone was not met.
Task 7: Technology Transfer & Outreach 7.1 Technology-to-Market (T2M) Plan 7.2 Intellectual Property (IP) 7.3 Product / First-Market Fit 7.4 Manufacturing and Scale Up 7.5 Next Stage Funding	• Initial T2M Plan. The goal of this milestone is to develop and demonstrate an understanding of the various key considerations for attempting to commercialize a new technology. Deliverable: initial T2M plan will be submitted to ARPA-E and it will be presented to program director & T2M Advisor for approval. Actual Performance: (Completion date: 3/20/2018) This milestone was met. • T2M Staffing: Identify / engage / schedule the personnel resources to accomplish the tech-to-market work for the duration of the project. A consultant with relevant expertise in marketing and power electronics will be identified. The consultant will help the team in market study, product refinement, techno-economic analysis (TEA), competitive analysis, and identifying potential customers. Assess potential need for expertise in intellection property, market analysis, cost models, and manufacturing scaling.

Tasks	Milestones and Deliverables
	Actual Performance: (Completion date: 6/20/2018) This milestone was met. • Final T2M Plan: As the technology is explored and developed, some of the assumptions and facts that support the T2M plan evolve. This task revises a specific subset of the T2M plan that should incorporate progress to-date. T2M plan will be revised with a focus on areas where prior assumptions / conditions have changed. Deliverable: revised T2M plan will be submitted to ARPA-E and will be presented to program director & T2M Advisor for approval. Actual Performance: Due to limited budget and not being able to hire a Tech2Market consultant this milestone was not met. • IP Strategy. Describe new intellectual property you expect to create as part of this effort and your plans for protecting it. Determine if any new IP has been created and if invention disclosures are warranted. Deliverable: IP strategy presented to program director & T2M Advisor. Actual Performance: (Completion date: 3/20/2018) This milestone was met. • Invention Disclosures. IP activity including invention disclosures, patent applications, and full patent publications must be reported on a quarterly basis. Patent applications stemming from work performed in this project must be entered into the Federal iEdison system Actual Performance: (Completion date:12/20/2022) This milestone was met. • Contacting potential licensees. Potential licensees will be identified and invited to Northeastern University to learn about the proposed technology and see the prototypes Actual Performance: (Completion date:N/A) This milestone was partially met. Before the pandemic the PI and the patent office at Northeastern contacted several potential licensees. When the pandemic started these activities were paused. For almost a year we could not have any visitors. • Market Research. Identify potential market research sources. Market knowledge will be complied. Deliverable: Market research will be presented to program director & T2M Advisor Actual Performance: (Completion date:3/20/2019) This milestone was met. • Product hypothesis. Prepare product hypotheses and test them through direct conversation with potential customers. Deliverable:

Tasks	Milestones and Deliverables
	Product hypotheses requirements will be presented to program director & T2M Advisor. Actual Performance: (Completion date: 12/20/2019) This milestone was met. • Techno-Economic Analysis (TEA). Generate a model which provides insight into the trade-offs and interactions between product design, cost (including bill of materials), and performance. Deliverable: TEA model will be presented to program director and T2M Advisor. Actual Performance: (Completion date:8/1/2020) This milestone was met. • Competitive Analysis. Identify competitive products / approaches and compile their attributes (i.e., cost, performance, market share). Deliverable: competitive landscape analysis will be presented to program director& T2M Advisor. Actual Performance: (Completion date:8/1/2020) The milestone was met. • Supply chain development. Conduct supply chain analysis including identifying risks from suppliers. Identify areas where single sourcing may occur and what mitigations will be taken to combat. Complete manufacturing plan with input from potential stakeholder discussions. Describe how the prototype process could be scaled to meet first market demand and where early manufacturing could take place. Present findings to PD and T2M Advisor. Actual Performance: (Completion date: 8/1/2019) This milestone was met. • Production process flow. Report on proposed manufacturing/assembly process flow (including yields, BOM, etc. updated form TEA) and draft product datasheet which could be shared with potential customers/investors Present the documents to the PD and T2M Advisor Actual Performance: (Completion date: N/A) This milestone was not met. • Goals and Resource Needs. Map out next stage goals and resource needs. Address both long-term and near-term, first-market applications. Deliverable: Analysis of next stage goals and resource needs will be presented to program director & T2M Advisor. Actual Performance: (Completion date: N/A) This milestone was not met. • Identify Potential Resources. Identify appropriate next stage funding sources. Address both long-term and near-term, first-

Tasks	Milestones and Deliverables
	market applications. Deliverable: Analysis of potential next stage funding sources presented to program director & T2M Advisor. Actual Performance: (Completion date: 6/20/20) This milestone was met. • Resource Engagement. Engage with potential next stage funding sources. Address both long-term and near-term, first-market applications. Deliverable: Engagement plan including list of potential engagements, rationale, and timeline presented to program director & T2M Advisor. Actual Performance: (Completion date: 9/20/20) This milestone was met. MassCEC funding: New application of universal converters: electric vehicle (received) NSF CAREER award: More research on this universal converter and other classes of universal converters for microgrid and renewable energy systems (received) STTR Proposal with Galey Power (rejected) SBIR Proposal with Galey Power (in-preparation) Next stage plans: Working with DOE, Army, Navy, etc. for testing the converter in relevant environment

Project Activities

Fig. 1 depicts the schematic of the proposed universal converter. This converter is a single-stage configuration, which can use high frequency transformer for isolation regardless of input and output. This converter also eliminates the need for large electrolytic capacitors. Using a series capacitor allows us to add a transformer to the link when galvanic isolation is needed. in this case the link capacitor must be split into two capacitors one at the primary and the other at the secondary. In each switching cycle the link capacitor is charged from the source (or the sources when we have a multi-phase source or several sources), and then it will be discharged into the load or loads. Given the high frequency of operation the ac sources and loads act similar to dc sources and loads in each switching cycle. By allowing the link capacitor to have high voltage ripple, the link capacitance can be significantly reduced.

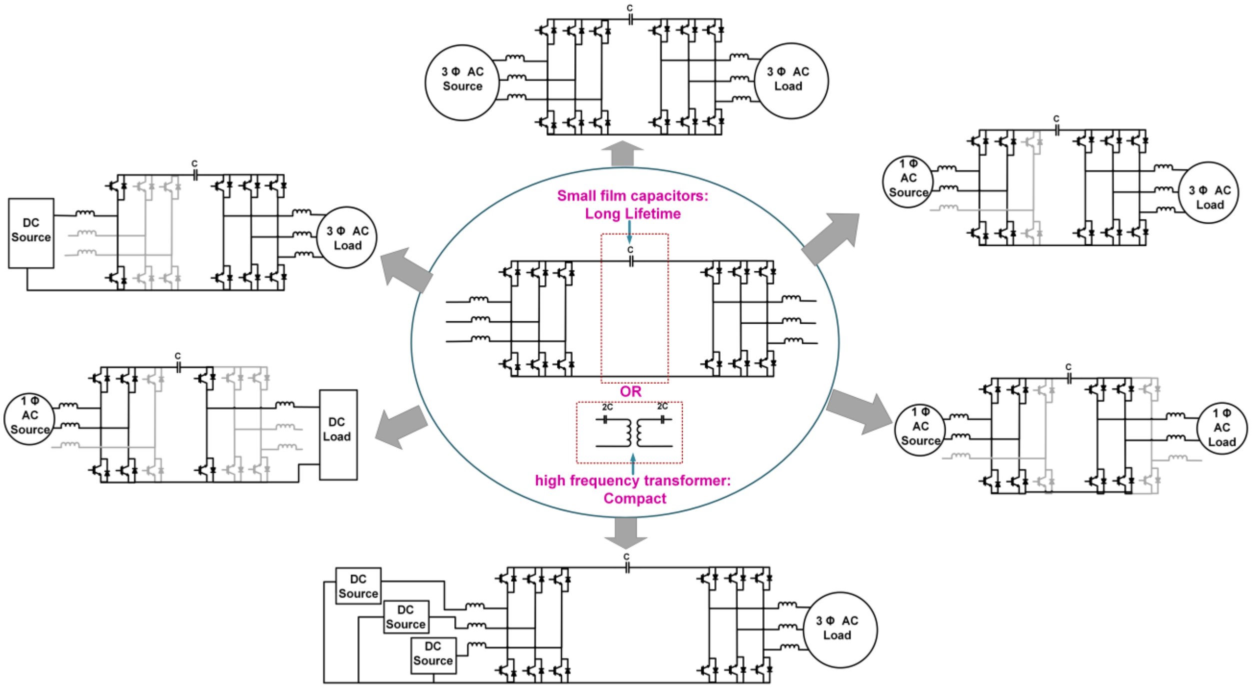

Figure 1. Proposed universal converter

During the first year of the project the team focused on the following tasks:

- Designing the gate driver
- Filter Design
- Fabricating a Universal prototype
- Simulating and preliminary testing of the universal converter as a single-phase inverter for residential PV system (330 W)
- Simulating and preliminary testing of the universal converter as a single-phase ac to three-phase ac converter for residential motor application (2.5 kW)

During the second year of the project the team carried out the following major tasks:

- Testing the universal converter as a single-phase inverter for residential PV system (330 W), and validating maximum power point tracking (MPPT), unity PF control, active and reactive control
- Testing the universal converter as a single-phase ac to three-phase ac converter for residential motor application (2.5 kW), and validating V/Hz control
- Simulating the universal converter as a multi-module single-phase inverter for residential PV system (1 kW)
- Simulating the universal converter as a three-phase ac to three-phase ac converter for wind application (10 kW)

During the third and fourth years of the project the team faced some problems due to COVID-19 pandemic, lack of personnel, and eventually lack of budget. Therefore, the final tasks were slightly modified. The team accomplished the following tasks during the last two years:

- Designing and simulating the universal converter as a three-phase ac to three-phase ac converter for industrial motor drive application (10 kW)

- Testing the universal converter as a three-phase ac to three-phase ac converter for industrial motor drive application (2 kW)

Fig. 2 represents the experimental results of the universal converter when it operates as a single-phase inverter for residential PV system. Parameters of the system are listed in Table II.

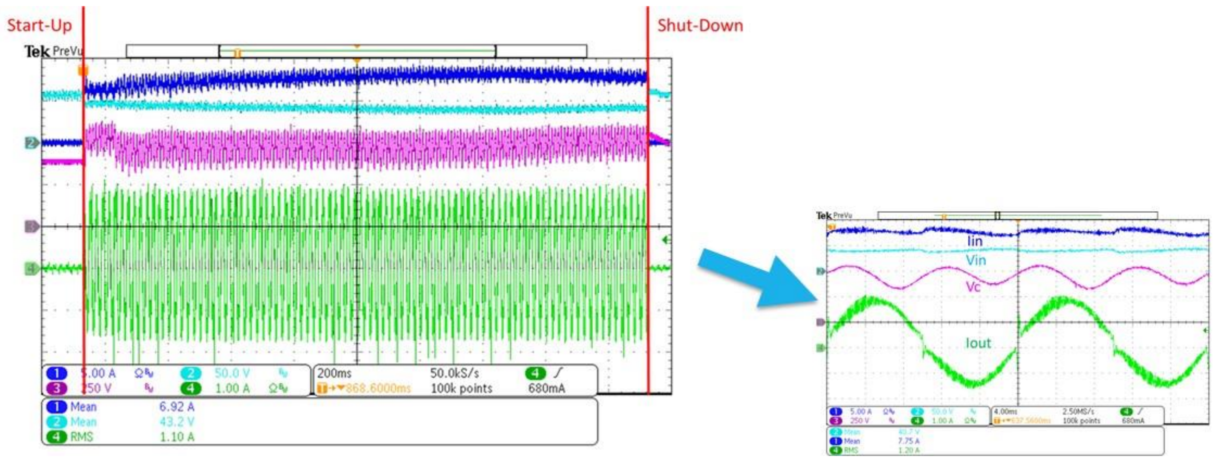

Figure 2. Experimental results corresponding to residential PV inverter

Table II. Parameters of the residential PV inverter

Parameter	Value
Input voltage	42 V
Output voltage	240 V
Link capacitance	10 µF
Switching frequency	40 kHz

Fig. 3 shows the experimental results of the universal converter operating as a single-phase ac to three-phase ac converter for residential motor drive application. Parameters of this system at listed in Table 2.

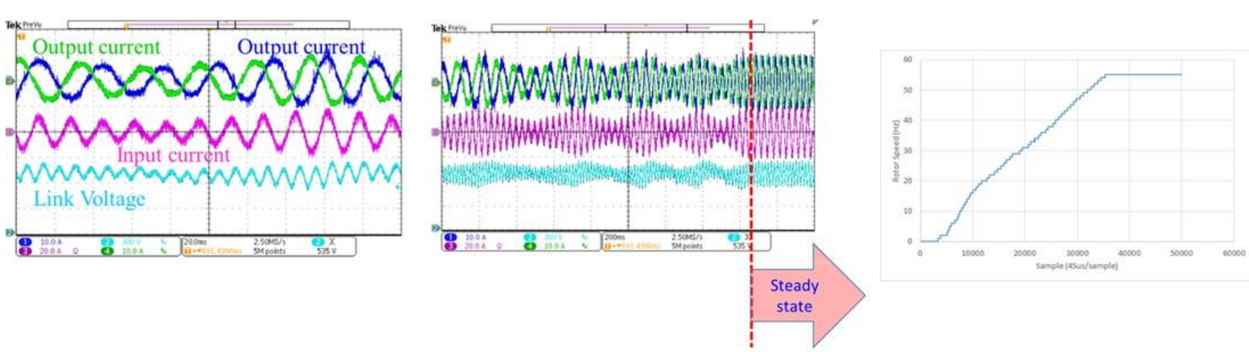

Figure 3. Experimental results corresponding to residential motor drive system

Table III. Parameters of the residential motor drive converter

Parameter	Value
Input voltage	208 V
Output voltage	208 V
Link capacitance	20 µF
Switching frequency	40 kHz

Fig. 4 depicts the experimental results of the three-phase ac to ac converter operating at 1920 W. parameters of the system are listed in Table IV.

Table IV. Parameters of the Three phase AC-AC converter

Parameters	Values
Link Frequency	40kHz
Link Capacitance	150nF
Link Inductance	3.3uH
Input L-N Voltage	83V, 60Hz
Output L-L Voltage	138V, 60Hz

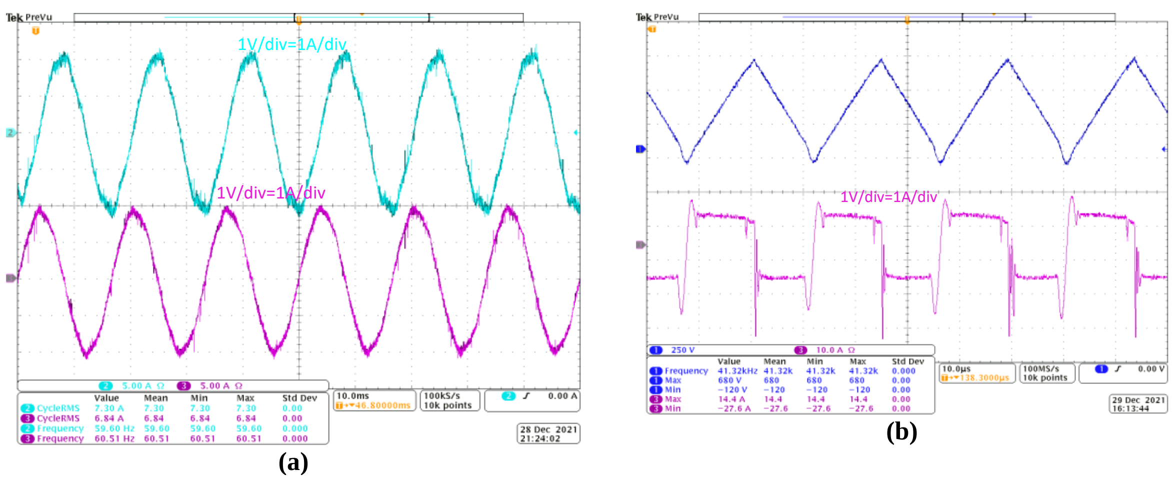

Figure 4. Experimental results corresponding to three-phase AC-AC converter: (a) input current (top) and output current (bottom), (b) link voltage (top) and link current (bottom).

Table V compares the target and actual values of efficiency and weight for different configurations. It must be noted that the fabricated converters were heavier than the target values; since, due to limited time, off-the-shelf inductors were used instead of customized designed and fabricated inductors.

Table V. Target and actual attributes of the proposed converters

Application	Target weight	Calculated weight of inductor cores and capacitors	Target efficiency	Measured or simulated efficiency
Single- phase ac to three-phase ac converter (2.5 kW)	2 kg	1.7 kg	97%	Using 1700 V SiC MOSFETs: 96.1% (measured) Using 3300 V SiC MOSFETs: 97.12% (simulated)
Single-module PV inverter (330 W)	2 kg	0.378kg	95%	95.9% (measured)
Three-module PV inverter (1 kW)	2 kg	0.991 kg	95%	96.5% (simulated)
Hybrid PV/Battery inverter (6 kW)	2 kg	1.945 kg	97%	97.1% (simulated)
Three-phase ac-ac converter (10 Kw)	2 kg	1.99 kg	97%	96% (simulation)

Project Outputs

A. Journal Articles

1. M. Khodabandeh, B. Lehman, and M. Amirabadi “A single-phase ac to three-phase ac converter with a small link capacitor”, IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10051-10064, Sept. 2021.
2. Xinmin Zhang, Masih Khodabandeh, Mahshid Amirabadi, Brad Lehman, “A Simulation-Based Multi-Functional Differential Mode and Common Mode Filter Design Method for Universal Converters”, IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 1, pp. 658-672, March 2020.
3. Masih Khodabandeh, Ehsan Afshari, and Mahshid Amirabadi, “A Family of Cuk-, Zeta-, and SEPIC-based Soft-Switching DC-DC Converters”, IEEE Transactions on Power Electronics, vol. 34, pp. 9503 - 9519, 2019.

B. Papers

1. Junhao Luo, Khalegh Mozaffari, Brad Lehman and Mahshid Amirabadi, "Parallel Capacitive-Link Universal Converters with Low Current Stress and High Efficiency", presented at 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, Canada, October 2021.
2. Masih Khodabandeh and Mahshid Amirabadi, "A Soft-switching Single-stage Zeta-/SEPIC-based Inverter/Rectifier", presented at 2020 IEEE Applied Power Electronics Conference and Exposition (APEC).
3. Masih Khodabandeh and Mahshid Amirabadi, "Cuk-derived five-level T-type inverter (CD-5LT2I)", presented at 2020 IEEE Applied Power Electronics Conference and Exposition (APEC).
4. Xinmin Zhang, Mahshid Amirabadi, Brad Lehman "A Generalized Swinging Bus Controller for Single-Phase PV Inverters to Eliminate Electrolytic Capacitor and Achieve Reactive Power Capability", presented at 2020 IEEE Applied Power Electronics Conference and Exposition (APEC).
5. Xinmin Zhang, Mahshid Amirabadi, Brad Lehman, "A Single-Phase PV Inverter with Swinging Bus Controller to Eliminate Electrolytic Capacitor and Achieve Reactive Power Generation Capability", presented at 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, Sep. 2019.
6. Xinmin Zhang, Mahshid Amirabadi, Brad Lehman, "A Generalized Simulation-Based Multi-Functional Differential Mode and Common Mode LCL Filter Design Method", presented at IEEE Workshop on Control and Modeling for Power Electronics, IEEE COMPEL 2019, Toronto, Canada, June 2019.
7. Xinmin Zhang, Mahshid Amirabadi, Brad Lehman, "A Long-Lifespan Single-Phase Single-Stage Multi-Module Inverter for PV Application", IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, 2018, pp. 6103-6109.
8. Masih Khodabandeh and Mahshid Amirabadi, "Capacitive-Link Universal Converters with Low Voltage Stress and High Switching Frequency", 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 7209-7215.
9. Masih Khodabandeh and Mahshid Amirabadi, "A single-phase ac to three-phase ac converter with a small link capacitor", 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 3942-3948.
10. Masih Khodabandeh and Mahshid Amirabadi, "An Efficient Snubber Circuit for Soft-Switched Capacitive-Link Universal Converters", 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 2911-2917.

C. Status Reports

D. Media Reports

E. Invention Disclosures

F. Patent Applications

1. Mahshid Amirabadi, "Power conversion devices and control methods therefor," US Patent 10,250,120, issued April 2, 2019.
2. Mahshid Amirabadi, "Highly Reliable and Compact Universal Power Converter," US Patent 10,848,071, issued Nov. 24, 2020.
3. Mahshid Amirabadi, Masih Khodabandeh, Mojtaba Salehi, "Zata-based AC Link Universal Power Converter", provisional US patent filed in July 2022

G. Licensed Technologies

H. Networks/Collaborations Fostered

I. Websites Featuring Project Work Results

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

K. Awards, Prizes, and Recognition

Second Place Prize Paper Award, IEEE Transactions on Power Electronics, 2021, for:

M. Khodabandeh, B. Lehman, and M. Amirabadi "A single-phase ac to three-phase ac converter with a small link capacitor", IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10051-10064, Sept. 2021.

Follow-On Funding

Additional funding received from NSF and MassCEC (listed in Table V) will help the team to further explore this promising converter.

Table V. Follow-On Funding Received.

Source	Funds Committed or Received
MassCEC	$64,906
NSF	$393,226