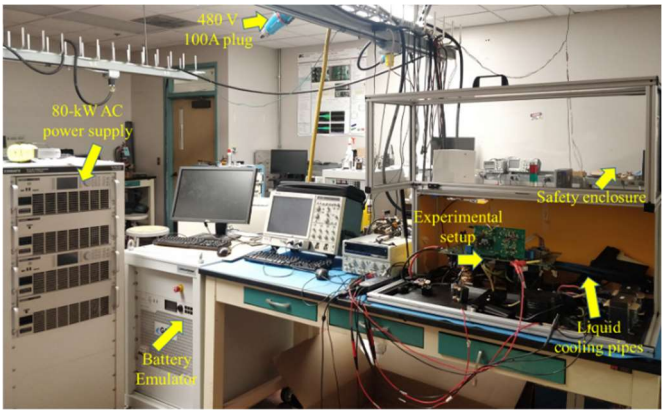
Final Scientific/Technical Report

UNIVERSITY OF ILLINOIS CHICAGO

LESES

Final Scientific/Technical Report
Universal Battery Supercharger
DE-AR0000903



Award:	DE-AR0000903
Lead Recipient:	University of Illinois Chicago (UIC)
Project Title:	Universal Battery Supercharger
Program Director:	Dr. Isik C. Kizilyalli
Principal Investigator:	Dr. Sudip K. Mazumder
Contract Administrator:	Advanced Research Projects Agency - Energy (ARPA-E) U.S. Department of Energy
Date of Report:	September 26, 2022
Reporting Period:	December 21, 2017 – May 31, 2022 (with NCE)

Public Executive Summary

During the course of the UBS project a dc-fast charger was developed to be used in off board high power charging stations. High efficiency is targeted to reduce the charging price for the consumer while reducing the charge time. In the meantime, the size of the converter is minimized so that it could be used in small spaces and potentially urban areas. The topology is modular, and the power level can be expanded for charging higher power vehicles like trucks and buses. During the course of this research several key technologies was developed in LESES that improve the performance of the power electronics system used in EV charger. Integrated magnetics was developed for DMCR to improve the power density as well as efficiency of the magnetic components which is one of the main bottlenecks of EV development. Triangular mode EV current conduction mode is using to perform soft switching (increase efficiency) without adding any new components to the existing topology. Passive and active damping are developed to suppress the interaction between grid and converter, stabilizing the control system. Further numerous other technical problems have been solved to pave the way for even higher performance converters in the future.

Acknowledgements

This work was supported by Advanced Research Projects Agency Energy, U.S. Department of Energy, under Award DE-AR0000903 in the CIRCUITS program monitored by Dr. Isik Kizilyalli. We also the acknowledge the services of the following students: Nikhil Kumar, Moien Mohamadi, Ankit Gupta, Anik Desai, Debanjan Chatterjee, Shantanu Gupta.

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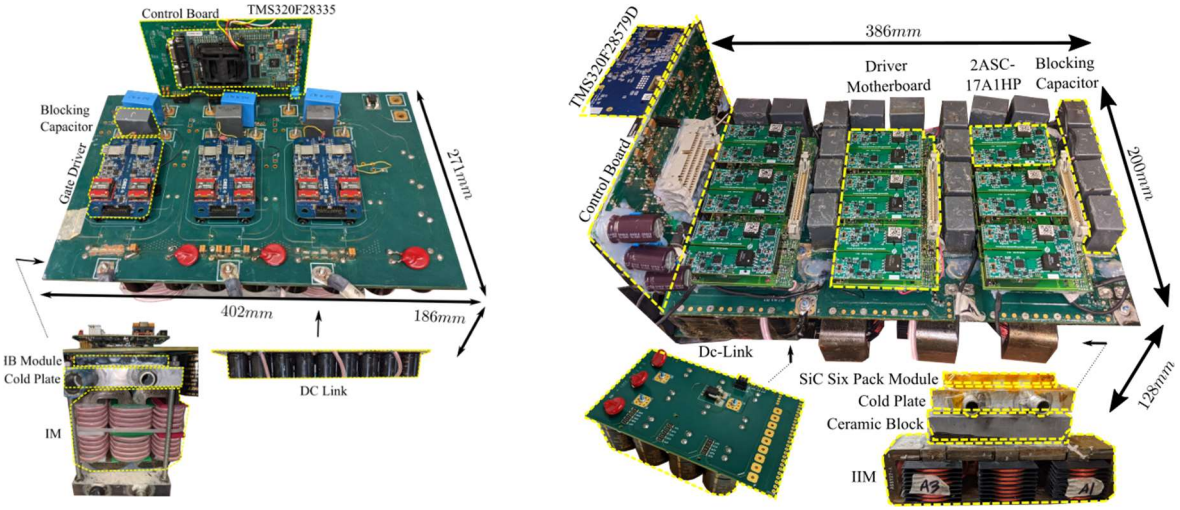
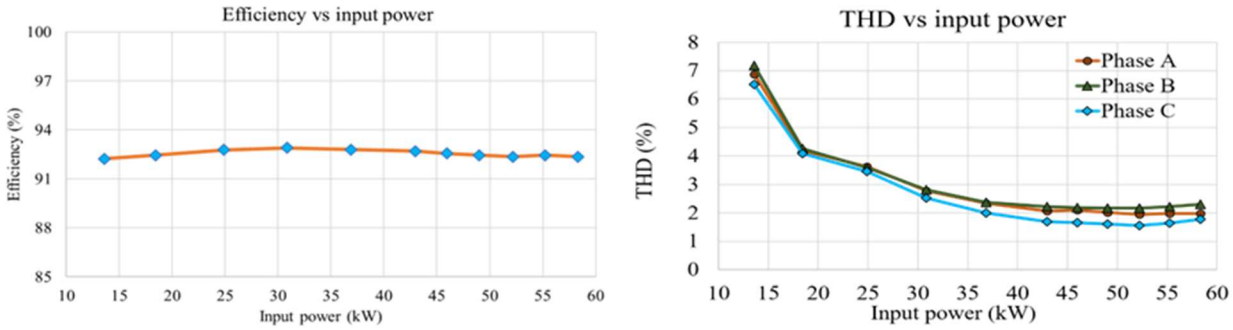
Accomplishments and Objectives

The objective of the UBS project was to develop a 60 *k*W battery dc-fast charger to simultaneously meet efficiency and power density/specific power requirements. First iteration of the UBS realized at 60kW is shown in Figure 1(a). The efficiency and THD with power curves are shown in Figure 2(a) and (b) respectively. In Figure 3 a three phase time domain results are presented at rated power. The first iteration was not able to achieve the desired efficiency therefore a soft switching variation was developed as shown in Figure 1(b). The efficiency and THD of this version and shown Figure 4(a) and (b). The temporal waveforms at low power are also shown in Figure 5.



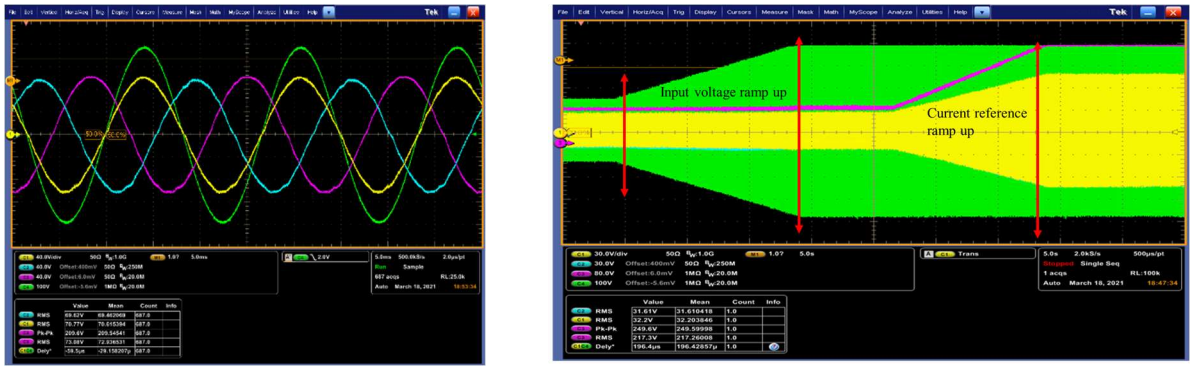
(a) (b)

Figure 1 UBS prototype (a) hard switched (b) soft switched.



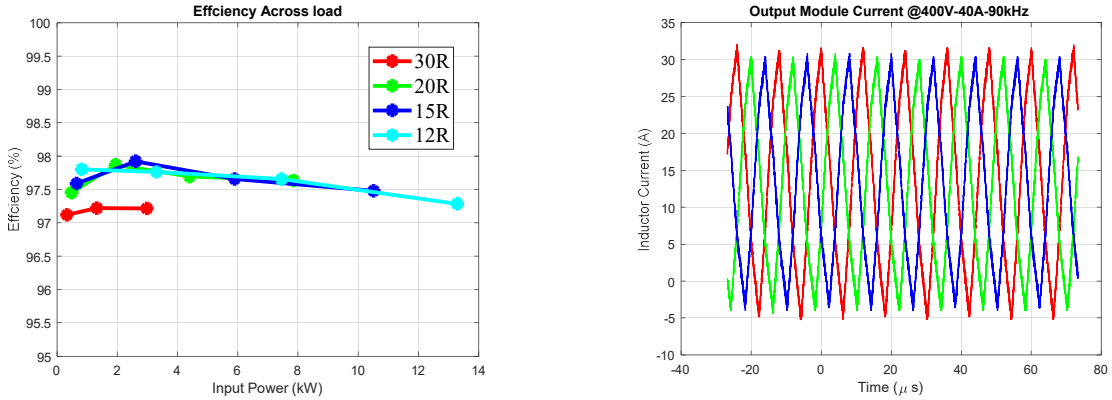
(a) (b)

Figure 2 Hard-switching experimental parametric results (a) efficiency (b) total harmonic distortion.



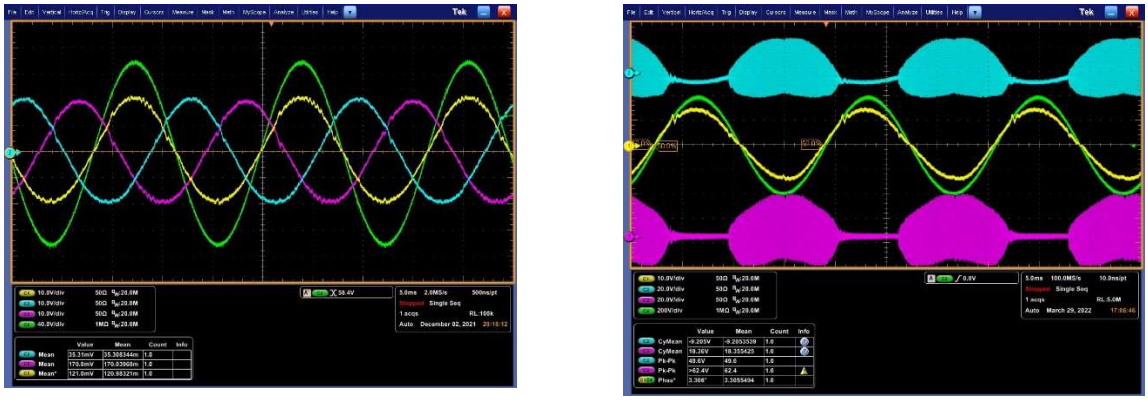
(a) (b)

Figure 3 (a) Steady state time domain results of the three-phase input current and phase A input voltage. The yellow curve is phase A current (40 A/div), the blue curve is phase B current (40 A/div), the purple curve is phase C current (40 A/div) and the green curve. (b) Sequence of increasing power on the UBS setup from 20% of the rated power to the rated power.



(a) (b)

Figure 4 (a) Single module efficiency of soft switching prototype (b) three level integrated interleaved inductor current



(a) (b)

Figure 5 (a) Steady state time domain results of the three-phase input current and phase A input voltage. The yellow curve is phase A current (10 A/div), the blue curve is phase B current (10 A/div), the purple curve is phase C current (10 A/div) and the green curve phase- neutral voltage of phase A (40v/div). (b) Sequence of increasing power on the UBS setup from 20% of the rated power to the rated power. (b) time domain inductor ripple in triangular conduction mode. The yellow curve is phase A current (10 A/div), the blue curve is phase A, ac-side inductor current of sub-module 1 (20 A/div), the purple, is the dc-side inductor current of sub-module 1(10 A/div) and the green curve phase- neutral voltage of phase A (200V/div) .

This award allowed UIC to pursue a transformerless charger topology and demonstrate some objectives. The focus of the project was on building a three-phase integrated magnetics based differential-mode rectifier technology for use as a dc charger.

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: Project Management and Development of work plan	Q1: Work plan finalized **Actual Performance:** (Completion date: 03/31/2018) Work plan was finalized along with tasks and milestones before the project was awarded. Q1: Impact Sheet **Actual Performance:** (Completion date: 03/31/2018) Impact sheet outlining the existing technology and IP held by the principal investigator and team. The motivation for developing the UBS according to the market and technology trends are outlined. potential of the project is described in detail for its impact on the future of the EV charging. Q12: Impact Sheet **Actual Performance:** (Completion date: 12/31/2020) The impact sheet is drawn detailing the technology opportunity, impact pathway, and long term impact of the project. The publications and IP resulted from the project is presented.
Task 2: UBS module and three-phase system design and validation 2.1 UBS module and system power stage 2.2 UBS module and system control	Q3: (M2.0.1) Design parametric, performance, control projections and analysis **Actual Performance:** (Completion date: 06/30/2018) UBS module and its characteristics is introduced with experimental DP test results. Gate driver is described with its specification and protection features. The integrated magnetics' design and characteristics is outlined accompanied by FEA simulation. All capacitors are designed with analytical and circuit simulation tools. The thermal mitigation system is design, and a small prototype is fabricated and test. The CAD layout of the system is designed.

Tasks	Milestones and Deliverables
2.3 UBS module and system protection 2.4 UBS module and system performance	Q3: (M2.0.1) Design parametric, performance, control projections and analysis **Actual Performance:** (Completion date: 06/30/2018) The control architecture of the UBS system is described in detail and verified with simulation. Q3: (M2.0.2) Operational analytical feasibility of the UBS **Actual Performance:** (Completion date: 06/30/2018) The protection strategy and mitigation for leakage current, one terminal fault is described and verified using simulation. Q4: (M2.0.3) Scaled power experimental feasibility of UBS **Actual Performance:** (03/31/2019) Experimental setup is fabricated and tested for the scaled power UBS. The system is tested single phase and 3-phase. The experimental results presented in time domain at 208Vrms, 100kHz, 8Apeak, and 2kw. The performance metrics are presented as parametric plots with power for two cases of integrated and discrete magnetics. The minimum THD is 1.1%, maximum power factor 0.995, and maximum efficiency is 92%. (12/31/2018). The 3kW results are presented at 208 Vrms, 8.5 Arms, and 100 kHz. The performance matrices were THD of 3.1%, power factor of 0.998, and efficiency of 92.2%.
Task 3: UBS experimental hardware and software design, packaging, fabrication, characterization, and operational feasibility	Q5: (M3.0.1) UBS module experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of Gen-1 SiC module specifications to achieve targeted performance. **Actual Performance:** (Completion Date: 03/31/2019) The SiC power MOSFET (Gen-1) is characterized with sweeping in gate resistance and case temperature. Device losses and ringing performance is presented. Rated power integrated magnetic is designed and fabricated using iron

Tasks	Milestones and Deliverables
3.1 Device and Gen-1 SiC module specification 3.2 Thermal realization 3.3 Magnetic realization 3.4 Gate driver realization 3.5 Protection realization 3.6 Power stage realization 3.7 Control stage realization 3.8 UBS module integration	powder cores (Gen-1). Rated power CAD layout and thermal design and optimization is presented (Gen-1). Q6: (M3.0.2) UBS module experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of magnetics design and characterization results; thermal design and characterization results; PCB schematic designs for power and control stages and board layouts and bill of materials **Actual Performance:** (Completion date: 06/30/2019) Magnetic design and specification is presented under this milestone. Thermal analysis design, and manufacturing details and considerations has been presented. PCB design for the power and control stage of the module is presented. Details of thermal and magnetic design optimization is presented for rated power. The analytical losses are calculated to be 174 W per module at rated power. The integrated magnetics are tested experimentally at 9 kW. Q7: (M3.0.3) UBS module experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of gate driver design and characterization results; protection design and characterization results. **Actual Performance:** (Completion date: 09/30/2019) Under the task 3.4 and 3.5, ac-side faults that includes overvoltage, overcurrent, and short-circuit faults in each phase, phase-phase has been tested. Dc-side faults such as overvoltage and short-circuit at dc-bus have been tested with mitigation time of 150 ns. Further, to shut down the PWM supply from gate driver and isolation of the UBS from input and output in the event of any fault is validated. Multiple fault scenario and characteristics are tested. Q8: (M3.0.4) UBS module experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of UBS module characterization, operational feasibility, and performance validation's module characterization, operational feasibility, and performance validation. **Actual Performance:** (Completion date: 12/31/2019) Experimental results displays the UBS operation feasibility at 20 kW. In this milestone, results regarding performance of the UBS at rated power is provided. A detailed outline of efficiency, power density, specific power challenges and mitigation strategy employed are provided. The UBS module meets at least 50% of final target for power density and specific power. Q8: (M3.0.5) UBS module experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for

Tasks	Milestones and Deliverables
	approval of module control software and results; Package layout design; Module experimental operational characterization and performance results: Peak efficiency > 95% at rated module power of 20 kW using SiC MOSFET module; Control bandwidth » 3 kHz at rated module power 20 kW using DSP operation; Start-up, transient, fault-handling response validations; Gate driver duty-cycle following: 10-90%; magnetic inductances for reduced current ripple; DSP code execution time ≤ 4us; Assessing thermal, device level inefficiencies. The prototype demonstrator must achieve at least 50% of the final targets for power density and specific power metrics. The testing will be at lab bench scale The experimental apparatus is expected to comprise 3-phase AC source, UBS AC/DC converter, load emulator Testing for voltage, current, and frequency will be using isolated ground oscilloscopes will be calculated using math operations in the scope and harmonics will also be determined using the scope Power factor will be determined using isolated ground scope or power analyzer Efficiency will be calculated using isolated ground scope or power analyzer Control bandwidth will be assessed using isolated scope or network analyzer Thermal assessment will be carried out using thermal imaging instrument **Actual Performance:** (Completion date: 12/31/2019) Due to discontinuation of the original SiC MOSFET from Wolfspeed, an alternative approach of is pursued with SiC JFET module. Integrated magnetics' size is reduced using a new material and core geometry. The UBS module is tested at 20 kW with efficiency of 95.02%.

Tasks	Milestones and Deliverables
Task 4: Three-phase UBS experimental charger system hardware and software designs, packaging, fabrication, system characterization, and system operational feasibility 4.1 UBS multi-module system layout 4.2 Power stage realization 4.3 Control software realization 4.4 UBS integration 4.5 Test setup 4.6 UBS testing	Q10: (M4.0.1) UBS three-phase system experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of system package layout design to achieve targeted performance levels. **Actual Performance:** (Completion date: 06/30/2020) Work towards this milestone has been completed. System package layout for the UBS is presented in the report. Final rated power board layout out and CAD design for the UBS is presented. An alternative approach is also being pursed simultaneously using DCM and soft switching to target turn on losses of the ac-side switch. An approach to reduce the size of the input filter and damp the resonance oscillation of the filter between the filter and the UBS is presented. Q11: (M4.0.2) UBS three-phase system experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of modified and final gate driver design and characterization results to meet final target performance specifications; protection design for system and characterization results; Embedded control software design for system and results. **Actual Performance:** (Completion date: 09/01/2020) PR compensators are used to control the input peak current with discontinuous modulation scheme. Work towards this milestone has been completed. Gate driver design and characterization has been presented in QR10. Protection tests for low power rectifier and high-power modules were reported QR7. Controls was also developed and tested in QR1-QR3. Q11: (M4.0.3) UBS three-phase system experimental operational characterization and functional feasibility: Presented to ARPA-E Program Director for approval of system PCB schematic designs and board layouts and bill of materials; System experimental operational characterization and performance validation results **Actual Performance:** (Completion date: 09/01/2020) The Work towards this milestone has been completed. Gate driver design and characterization has been presented in QR10. Protection tests for low power rectifier and high-power modules were reported QR7. Controls was also developed and tested in QR1-QR3. Q12: (M4.0.4) UBS three-phase system experimental performance characterization: Presented to ARPA-E Program Director for approval of final validation three phase charger operation at rated power and at 480 V (RMS) and line frequency (60 Hz); Power density: ≥ 100 W/in3with attempted 150 W/in3(without line protection units); Peak efficiency >

Tasks	Milestones and Deliverables
	95% at rated power with attempted » 98% at rated power; Three-phase input current THD at rated power ≤ 5% (at rated power); Specific power » 5 kW/kg; Cost: 5c/watt (in very large volume); Charger control bandwidth » 3 kHz; Charging time: ≤ 30 minutes at rated power The testing will be at lab bench scale The experimental apparatus is expected to comprise 3-phase AC source, UBS AC/DC converter, load emulator Testing for voltage, current, and frequency will be using isolated ground oscilloscope, THD will be calculated using math operations in the scope and harmonics will also be determined using the scope, Power factor will be determined using isolated ground scope or power analyzer, Efficiency will be calculated using isolated ground scope or power analyzer, Control bandwidth will be assessed using isolated scope or network analyze **Actual Performance:** (06/31/2022) The hard switching prototype presented at rated power (60 kW) and rated voltage (480Vrms). From 20% of the rated power to 100% of rated power, 1) efficiency stays between 92-93%, 2) THD is below 5% , and 3) power factor is ~0.99. Power density is ~50W/in3. To alleviate the performance matrices, soft switching prototype is developed. The power module is tested in dc mode with varying load exhibiting efficiencies between 97.5%-98% with peak efficiency of 97.97%. This is tested up to rated power with 2x-interleaved sub-modules. In the three-phase rectifier mode the converter is tested up to 10kW at 480Vrms exhibiting with 2x interleaved sub-module and sustained ZVS. The power factor is 0.99, THD of < 5%, and efficiency is between 96-98%. The power density would be 110 w/in3 at 60kW. Developing the power was progressing optimally but slowly due to multiple challenges in the power stage and feedback system. However, due t shortage of time the power is not increased further.

Tasks	Milestones and Deliverables
Task 5: Technology Transfer and Outreach 5.1 Technology to market plan 5.2 Intellectual property 5.3 product and first market 5.4 manufacturing and scale up 5.5 Next stage funding and impact	Q1: (M5.1.1) T2M Staffing: Identify a T2M point contact for the project Develop a roadmap for planned activities as defined in T2M Plan template provided by ARPA-E Include key considerations to maximize impact including commercialization strategy. **Actual Performance:** (Completion date: 03/19/2018) T2M staffing was decided before the project was awarded. The T2M effort as discussed in there will be led by PI Mazumder with assistance from Mr Krivchenia at UIC's Office of Technology Management (OTM). Initial T2M plan has been prepared. It will be e-mailed to ARPA-E and is also appended at the end of this report. Q1: (M5.1.2) 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: 03/19/2018) Impact sheet outlining the existing technology and IP held by the principal investigator and team. The motivation for developing the UBS according to the market and technology trends are outlined. potential of the project is described in detail for its impact on the future of the EV charging Q4: (M5.1.3) 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: Final T2M plan will be submitted to ARPA-E and will be presented to program director & T2M Advisor for approval. **Actual Performance:** (Completion date: 12/30/2018) Extensive T2M plan presented to the program director with detailing product concept, customer needs, market opportunity, technology potential, and relevant market research. The plan was outlined revolving around the value proposition of the UBS. Q1: (M5.2.1) 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: 03/19/2018) Performer states progress against the milestone and completion date. Should be as quantitative as possible.

Tasks	Milestones and Deliverables
	Q12: (M5.2.2) IP reporting: 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: 01/28/2021) Performer states progress against the milestone and completion date. Should be as quantitative as possible. Q5: (M5.3.1) Market research: Target market research, competitive landscape, & product hypothesis Techno-economic analysis inc. trade-offs/interactions of design, cost & performance. Present to PD and T2M advisor **Actual Performance:** (Completion date: 03/30/2019) initial research is done on the IP landscape. Value proposition of the UBS technology is described. Market research is carried out and potential partners are identified. The competitive technologies in the market are researched and compared with the UBS technology. Q6: (M5.3.2) Product hypothesis: Prepare product hypotheses and test them through direct conversation with potential customers including but not limited to Schneider Electric & Wolfspeed. Deliverable: Present product hypotheses requirements to PD and T2M advisor. **Actual Performance:** (Completion date: 06/30/2019) A tech alert is prepared along with a brochure for the UBS technology. Multiple meetings and sit-downs are conducted with, Infineon, ABB, Wolfspeed, Caterpillar, Boeing, and EPIR. More then 20 companies are also reached out through email. Q7: (M5.3.3) 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 PD and T2M Advisor. **Actual Performance:** (Completion date: 09/30/2019) With regard to the techno economic model, we have reached out to several groups to find someone who can do TEA on the proposed level 3 dc fast charger. Further, we need to have a discussion with the T2M lead (Danny) to clarify the scope of the TEA. This is beyond the capability of Dr. Mazumdar's Lab or UIC's OTM.

Tasks	Milestones and Deliverables
	Q8: (M5.3.4) Competitive analysis: Identify competitive products / approaches and compile their attributes (i.e., cost, performance, market share). Deliverable: competitive landscape analysis will be presented to PD & T2M Advisor. **Actual Performance:** (Completion date: 12/31/2019) Regarding the T2M, W\while Schneider Electric is a potential T2M partner, we have executed NDA with John Deere who has shown interest to explore T2M partnership, and NDA has been executed with Eaton also in that regard. In addition to the technical milestone, a cost breakdown of UBS based on current market, bulk purchasing, and projected market share is provided. The data has been consulted with the UBS component manufacturers. Under this millstone, a competitive analysis is done. UBS is compared with various commercially available EV chargers based on performance parameters such as efficiency, power density weight, and cost. A graphical and tabular representation of UBS performance is also provided. Q8: (M5.4.1) Supply chain development: Survey potential suppliers of new system components and compare processes, ability to scale, and other factors impacting product manufacture. Conduct supply chain analysis including identifying risks from suppliers. Identify areas where single sourcing may occur and what mitigations will be taken to combat. Present findings to PD and T2M Advisor. **Actual Performance:** (Completion date: 12/31/2019) Under this milestone, a supply-chain analysis is done. A new supplier United SiC for supplying SiC N-JFETs and Si FETs is identified. For UBS components, apart from primary supplier, some alternative suppliers have been identified. The primary suppliers CREE, DigiKey, Mouser etc. have ability to produce and distribute UBS components in bulk. Q9: (M5.4.2) Production process flow: Report on proposed manufacturing/assembly process flow (including yields, BOM, etc.) and draft product datasheet which could be shared with potential customers/investors. Include input from potential vendors including but not limited to Schneider Electric & Wolfspeed. Describe how the prototype process will be scaled to meet first market demand and where early manufacturing will take place. Complete manufacturing plan with input from industrial partners. Present the documents to the PD and T2M. **Actual Performance:** (Completion date: 03/19/2020) Performer states progress against the milestone and completion date. Should be as quantitative as possible.

Tasks	Milestones and Deliverables
	Q9: (M5.5.1) Draft next stage succession plan: Next stage goals for introducing product into market and resources required shall be identified. Deliver succession plan describing preferred approach e.g. licensing to or partnering with the stakeholder companies. Appropriate next stage private/public funding sources for both near-term first market applications and long-term strategy shall be detailed. Describe what resources and funding sources & timing needed for the next phase and get ready for technology deployment. Present Succession plan report to PD and T2M Advisor. **Actual Performance:** (Completion date: 03/19/2020) Performer states progress against the milestone and completion date. Should be as quantitative as possible. Q11: (M5.5.2) Complete follow on funding/post ARPA-E activity: Post ARPA-E business plans including licensing, company/partner engagements for product introduction with milestones shall be provided to maximize the technology impact in the market. Include aspirations of potential vendors. Summarize final follow on funding outcome for PD and T2M Advisor. Write an Impact Sheet for project that ARPA-E can share externally. **Actual Performance:** (Completion date: 09/01/2020) Work towards this milestone has been completed. Post award plans has been laid out for scale-up and NDA has been executed with industrial partners. A new PCT (international) patent application on the UBS technology has been filed by the University of Illinois at Chicago. S.K. Mazumder, N. Kumar, and M. Mohamadi, "Transformer-less, single-stage power module for off-board EV charging," PCT Patent Application# PCT/US2020/057743, 2020. (Original provisional patent application filed in 2019).

For projects involving computer modeling, provide a brief description of the model, key assumptions, how the model was validated, and whether or not the model and results were presented in peer-reviewed publications.

Project Activities

In the UBS a 60 *k*W dc fast charger is developed to achieve high power density, high efficiency, and high specific power simultaneously. Differential mode Ćuk rectifier (DMCR) using integrated magnetic (IM) and 1.7 kV SiC MOSFET modules are used to realize the UBS. First a low power prototype is developed to test the basic functionality of the DMCR for UBS application. This was followed by extensive testing in protection and scaling up the power to 60 *k*W. The first UBS realized by hard switching did not satisfy the efficiency metric due to excessive turn-on loss. Therefore, an alternative approach was proposed using triangular conduction mode to achieve

ZVS turn on though multi-level interleaved sub-modules per phase. To alleviate the increased number of components all the magnetics per phase is integrated in a single device and a six pack power MOSFET is used. A custom gate-driver motherboard is design specifically to operate all the power devices while maintaining the power density. The later approach achieved ~97% efficiency at lower power.

Project Outputs

A. Journal Articles

1. M. Mohamadi, N. Kumar, S. K. Mazumder and A. Gupta, "High Power Design Challenges for Differential-Mode EV Universal Battery Supercharger," in IEEE Transactions on Industry Applications, doi: 10.1109/TIA.2022.3152467.
2. M. Mohamadi, S. K. Mazumder and N. Kumar, "Integrated Magnetics Design for a Three-Phase Differential-Mode Rectifier," in IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10561-10570, Sept. 2021, doi: 10.1109/TPEL.2021.3066506.
3. N. Kumar, M. Mohamadi and S. K. Mazumder, "Passive Damping Optimization of the Integrated-Magnetics-Based Differential-Mode Ćuk Rectifier," in IEEE Transactions on Power Electronics, vol. 35, no. 10, pp. 10008-10012, Oct. 2020, doi: 10.1109/TPEL.2020.2981918.

B. Conference Papers

1. N. Kumar, M. Mohamadi and S. Mazumder, "High Performance Off-Board DC Fast Charger," 2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2021, pp. 1-7, doi: 10.1109/PEDG51384.2021.9494233.
2. M. Mohamadi and S. K. Mazumder, "Airgap-less Integrated Magnetic Array Using High Performance Magnetic Material in the EV Chargers," 2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2021, pp. 1-6, doi: 10.1109/PEDG51384.2021.9494220.
3. N. Kumar, M. Mohmadi and S. Mazumder, "Experimental Validation of Single-Stage Three-Phase Non-Isolated Cuk Rectifier," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 2744-2751, doi: 10.1109/ECCE.2019.8912485.
4. N. Kumar, S. K. Mazumder and A. Gupta, "SiC DC Fast Charger Control for Electric Vehicles," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), 2018, pp. 599-605, doi: 10.1109/ECCE.2018.8558208.

C. Status Reports

Nothing to report yet

D. Media Reports

Nothing to report yet

E. Invention Disclosures

2 patents were filed as captured below.

F. Patent Applications

[1] S.K. Mazumder, N. Kumar, and M. Mohamadi, "Three-phase differential mode converter," USPTO utility patent application number USSN 17/264,110, 2021.
[2] S.K. Mazumder, N. Kumar, and M. Mohamadi, "Transformer-less, single-stage power module for off-board EV charging," PCT Patent Application# PCT/US2020/057743, 2020. (Original provisional patent application filed in 2019).

G. Licensed Technologies

Nothing to report yet

H. Networks/Collaborations Fostered

Several companies interacted with

I. Websites Featuring Project Work Results

Nothing to report yet

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

Nothing to report yet

K. Awards, Prizes, and Recognition

IEEE Transaction on Power Electronics Second Place prize paper award in 2021 for the following paper: M. Mohamadi, S.K. Mazumder, and N. Kumar, "Integrated magnetics design for a three-phase differential-mode rectifier," IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10561-10570, 2021.

Follow-On Funding

Additional funding committed or received from other sources (e.g., private investors, government agencies, nonprofits) after effective date of ARPA-E Award.

Table 2. Follow-On Funding Received.

Source	Funds Committed or Received
NSF	$978,087 received (UIC is a subawardees)
DOE VTO	$2,000,000 concept paper submitted