**Multi-Port Energy Router Using Intelligent Transformers (MERIT) For Offshore Power Systems**

**PIs: Harish Krishnamoorthy and Kaushik Rajashekara**

**Overview and Background**:

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Starting 2018, the SSI, funded by TCEQ, placed significant emphasis on the power systems for offshore energy production, including subsea oil and gas, offshore wind, etc. The first project on ‘Subsea Power’ involved the design of high voltage DC (HVDC) circuit breakers and the associated power conversion for offshore energy applications. The second task of that 2018 project led to the development of a fault-tolerant isolated DC-DC based solid state transformer (SST) design as well as reliability prediction mechanisms in offshore electrical systems. The students who worked on these tasks were Dr. *Anindya Ray* and Dr. *Amin Sadat*, who are working in leading industries right now.

The success of those projects led to the subsequent funding from SSI/TCEQ for the project, titled, *Multi-Port Energy Router Using Intelligent Transformers* or in short, **“MERIT”**. The MERIT project was executed in 2 phases: 2021-22 and 2023-24. The main goal of the MERIT project is to *increase the safety and reliability of the HVDC power transmission and distribution systems*. The proposed techniques *improve the power quality* and *extend the lifetime* of the expensive power converters enabling low maintenance and low risk to personnel. It is observed that widespread implementation of the proposed synergies could *lead to over 50 % reduction in greenhouse gas emissions* in offshore power generation for subsea oil and gas extraction. The proposed techniques can further make the systems *compact and cost effective*, even for niche applications such as offshore wind and wave energy systems. The details of the two phases of the MERIT project are provided below.

**Phase-I: 2021-2022**

*MERIT: Interconnect Renewable Resources and Subsea Oil & Gas Factories via HVDC Link*

The Phase-I of the MERIT project proposed a system of multi-port energy routers using intelligent transformers to interface renewable resources and subsea O&G factories with the HVDC (or MVDC) Grid. In this project, we investigated combining the energy from wind, wave, floating PV panels and fuel cell - based generators, all located near the subsea factories, to power the loads. As part of this project, intelligent power converters were examined to enhance the power density, reliability and efficiency of the proposed MERIT system. SSTs were selected to enable seamless interconnectivity and interoperability between the various energy sources. This project also led to the investigation of how to optimally design and integrate SSTs into the MERIT system to have the best performance both during transient and steady state conditions. In this project, we also investigated the use of fast circuit breaker technology including the possibility of connecting superconducting fault current limiters to limit the current and protect the electrical system.

PhD Students in Phase-I: Dr. *Arnur Karbozov* and Dr. *Virendra Singh*

Post doc: Dr. *Mriganka Ghosh*

**Phase-II: 2023 - 2024**

*MERIT: Energy Management And Supervisory Control*

As continuation of the Phase 1 of the project (2021-22), we worked on the Phase-II of the project to develop energy management and supervisory control strategies for interfacing the renewable energy sources using the MERIT concept, which further helps to interconnect with the subsea loads and/or onshore systems via Medium Voltage DC (MVDC) or Medium Voltage AC (MVAC) grid. This research also advanced the state-of-the-art power converter and control technologies to enable seamless energy transfer between offshore renewable energy resources, subsea loads and the MV grid, even with long cables from the power inverter output to the subsea motor loads such as PM Motors, and also provide the necessary grid services in accordance with IEEE-1547. As part of this project, an energy router based on triple active bridge converter was investigated along with various control strategies for integration of various renewable energy sources. In addition, control strategies for controlling permanent magnet machines with long cables from the inverter were also investigated. This technology can be used in real-world applications once the energy companies decide to incorporate more renewable energy sources and permanent magnet electrical machines for subsea oil and gas extraction.

PhD Students in Phase-II: Dr. *Arnur Karbozov* and Dr. *Virendra Singh*

Post doc: Dr. *Tutan Debnath*

**Key Highlights and Major Outcomes:**

These projects funded by SSI via TCEQ (Restore Act) have had tremendous success over the last several years. A few critical highlights and outcomes are listed below.

1. Resulted in several major publications (directly or indirectly) as follows:
   1. A. Ray, S. N. Banavath, S. K. Pramanick, K. Rajashekara, ”A Coupled Inductor based Hybrid Circuit Breaker Topology for Subsea HVDC Transmission Systems”, in proc. 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 7142-7149.
   2. A. Ray, S. N. Banavath, K. Rajashekara, ”Coupled Inductor Based Hybrid DC Circuit Breaker Topologies for DC Grid Application”, in proc. IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, D. C, 2018, pp. 1116-1121.
   3. A. Ray, K. Rajashekara, S.N. Banavath, “Bidirectional Coupled Inductor Based Hybrid Circuit Breaker Topologies for DC System Protection”, IEEE APEC 2019, Anaheim, CA.
   4. A. Ray, K. Rajashekara, H. Krishnamoorthy, “Novel HVDC Power Transmission Architectures for Subsea Grid”, OTC 2019, Houston.
   5. A. R. Sadat, H. S. Krishnamoorthy and S. Yerra, "Isolated Multilevel HVDC Converter for Off-shore DC Distribution," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, USA, 2018, pp. 465-470.
   6. A. R. Sadat, H. Krishnamoorthy, K. Rajashekara, “Condition Monitoring of Power Converters in Extreme Environments”, OTC 2019, Houston.
   7. A. R. Sadat and H. S. Krishnamoorthy, "Fault-Tolerant ISOSP Solid-State Transformer for MVdc Distribution," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 6, pp. 6985-6996, Dec. 2021.
   8. A. Karbozov, M. G. Majumder, H. Krishnamoorthy and K. Rajashekara, "Medium Frequency SST Based Multiport Energy Routers for Subsea – Renewable Interconnection," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), Houston, TX, USA, 2022, pp. 416-421.
   9. A. Karbozov, M. G. Majumder, H. S. Krishnamoorthy and K. Rajashekara, "A Novel Control Strategy for Extending the ZVS Range of Triple Active Bridge Converter," 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022, pp. 1-6, doi: 10.1109/ECCE50734.2022.9947372.
   10. A. Karbozov, M. G. Majumder, H. S. Krishnamoorthy and K. Rajashekara, "Triple Active Bridge Based Multiport Energy Router for Subsea – Renewable Interconnection," in IEEE Transactions on Industry Applications, vol. 59, no. 4, pp. 4528-4538, July-Aug. 2023, doi: 10.1109/TIA.2023.3267031.
   11. A. Karbozov, H. S. Krishnamoorthy and K. Rajashekara, "Modular Multiport Converter Based Offshore Grid Architecture for Integrating Renewables and HVDC Grid," 2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Shanghai, China, 2023, pp. 111-116, doi: 10.1109/PEDG56097.2023.10215234.
2. Through the SSI projects, the team funded four Ph.D. students – Anindya, Amin, Arnur, and Virendra. Also, supported two post-doctoral fellows – Mriganka and Tutan. All of them are currently in successful full time jobs right now. More details are below.
3. The industry collaboration developed through these projects led to the initiation of the *PEMSEC Consortium*, which is running successfully.
4. The UH power team has been recognized by international media (and other agencies) as a leader in the area of power conversion and safety systems in offshore electrification. Dr. Rajashekara earned the prestigious *IEEE Medal For Environmental And Safety Technologies*, including subsea systems. Dr. Krishnamoorthy was recognized as an *OTC Emerging Leader* by the Offshore Technology Conference in 2022. He was also invited to comment about offshore power systems by IEEE Spectrum (the article here: <https://spectrum.ieee.org/underwater-power-cable>).
5. Findings from these project served to establish the much needed preliminary results that led to 2 major research grants for the PIs:
   1. *Dr. Harish Krishnamoorthy*: Early Career Research Fellowship (ECRF) in 2023-2024 funded by the Gulf Research Program (GRP) of the U.S. National Academy of Science, Engineering, and Medicine (NASEM).
   2. *Dr. Harish Krishnamoorthy, Dr. Kaushik Rajashekara*, *Dr. Ram Seetharam*,and others: Funded by the U.S. Department of Energy’s (DoE) NETL (GRANT-13952882\_ROICE, Office of Fossil Energy), which officially started on 29 May 2024 (until May 28, 2026).

**Testimonial from past students who participated in the SSI-Power projects**:

(1) Dr. Anindya Ray



*My thesis focused on the exploration and design of subsea power distribution and protection architectures. Under this work frame, I proposed new HVDC architectures for subsea power distribution and validated them by real-time simulation results in Typhoon HIL. I also extensively worked on the design and hardware prototype development of ZCS hybrid DC circuit breakers. The third part of my work focused on the design and hardware development of high-current gain resonant inverters for subsea pipeline heating.* (Research Topic)

*During my work at UH in the Subsea Institute-sponsored project, I got a chance to work on DC circuit breakers, a then-new topic in the domain of power electronics. This work immensely helped me to improve my design-oriented knowledge and hardware development skills. I further honed my learning, under Prof. Rajashekara's guidance, on the topic of resonant power converter design. I also learned real-time simulation from this project. All these helped me in my future roles at Sandia National Laboratories and JLR.*

*I am working as a Lead Power Electronics Engineer in the charging HW group at Jaguar Land Rover Technology Business Services India (JLRTBSI) Pvt. Ltd., which is one of the key engineering centers for Jaguar Land Rover (JLR). My role mainly focuses on the design and delivery of the HV-LV DC-DC converter for 12V systems in JLR EVs. This work requires power converter design skills, which were shaped and improved under the guidance of Prof. Rajashekara at the University of Houston.* (Current Work)

*I would like to thank Prof. Rajashekara for giving me a chance to work on novel power electronics topics and helping me build my skills as a power electronics engineer. I enjoyed and cherished my time at the PEMSES Lab, UH. I wish all the success to the current and future researchers and the faculties at PEMSEC.*

(2) Dr. Amin Sadat

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*My main topic was to develop fault-tolerant solid-state transformer (SST) structure to combine the benefits of higher power density and robustness in medium-voltage DC (MVDC) electric distribution systems proposed in this dissertation. A SiC-MOSFET-based 6 MW, 36/6 kV ISOSP (input series output series-parallel) modular stacked DC/DC SST is proposed using medium frequency (MF) transformer isolation. This structure renders the system with fault tolerance and the capability to operate normally even in a partial fault condition.*

*During my research, I deeply understood SiC-MOSFETs in medium-voltage DC (MVDC) electric distribution systems, leading me to design and validate a fault-tolerant DC/DC converter for subsea applications. This knowledge enhanced my expertise in high-efficiency power conversion and robust system design. The experience was beneficial as it gave me practical insights into cutting-edge technologies and improved my problem-solving skills in complex engineering scenarios.*

*I am a senior power electronics engineer at Garrett Advancing Motion, a global leader in automotive technology. I am an R&D lead engineer for traction inverter design. My work experience includes the development of power electronic technologies for eBoosting, eCompressor, and Power Train applications. With the experience of completing a Ph.D. degree in power electronic engineering at PEMSEC, I lead the research and development of innovative power electronic products for electrified powertrain applications.*

(3) Dr. Arnur Karbozov:



*During my PhD at the University of Houston, my research focused on designing a Multiport Energy Router with Intelligent Transformers (MERIT) for subsea systems. The objective was to develop power conversion architectures to integrate renewable energy sources, such as wind energy, with energy storage systems, and the onshore grid to power subsea loads. This work aimed to enhance the efficiency and reliability of power transmission and distribution in subsea environments.*

*Through my involvement in the different projects at UH, I gained extensive knowledge of subsea electrical systems and power conversion systems for renewable energy sources. Specifically, I developed expertise in isolated DC-DC converters and their control design. This experience led to the publication of several papers in IEEE conferences and journals.*

*Currently, I am working at a Bay Area startup, where I focus on the electrification of residential houses in the US. The skills and experiences I acquired during my time at UH were instrumental in securing an internship, which eventually led to a full-time position. My work at UH provided a solid foundation in advanced power conversion technologies and their practical applications.*

(4) Dr. Virendra Singh:



*My research focused on the performance enhancement of sensorless control of permanent magnet motors used in long cable subsea applications. The goal was to improve the efficiency and reliability of these motors for subsea operations like drilling, pumping, and boosting, by addressing the challenges associated with sinewave filter, transformer, and long cable. The control techniques such as initial position detection, voltage compensation, parameter estimation, and high-frequency injection were incorporated to achieve high-performance control.*

*I learned about the unique challenges faced by the subsea industry due to harsh environments and complex electrical architectures. This research has been beneficial in developing solutions for reliable motor start and efficient control throughout the speed range, which can save energy and improve reliability in subsea projects. This experience provided me with deep insights into formulating and implementing solutions that are directly applicable to the subsea industry.*

*I am currently working at an energy and technology service company that supports tools for upstream oil and gas extraction, both onshore and offshore. My research at the University of Houston has prepared me to handle the reliability issues caused by the harsh subsea environment, including temperature and pressure variations. The knowledge and skills I gained have been directly applicable to my current job, allowing me to contribute effectively to improving subsea equipment performance. The research experience deepened my understanding of the complexities of motor control in subsea environments and provided me with practical insights that are directly applicable to my current job, enhancing my ability to contribute to the industry.*