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EPIC RFI docket 23-ERDD-01 Direct Current Power Systems

Additional submitted attachment is included below.

To: California Energy Commission
Commissioners and Staff
EPIC Program
Docket Unit, MS-4
715 P Street
Sacramento, CA 95814-5512

Date: 7 August 2023

Re: Docket No. 23-ERDD-01
Request for Information (RFI): Direct Current Power Systems

Background: The California Energy Commission (CEC) is gathering information for a potential future grant funding opportunity (GFO) focused on research needed to enable efficient power delivery for direct current (DC)-based electrical systems. The purpose is to help define critical research needs in this area and identify high-impact use cases that a future research GFO may target. Ricardo, Inc., thanks the California Energy Commission for the opportunity to respond to the RFI in order to inform staff regarding current developments in DC-based power systems, how they can improve system efficiency and achieve energy cost savings by eliminating power conversions, and research required to enable these systems to be developed and implemented.

Responses to CEC Questions: Ricardo is providing answers to the following questions posed by CEC in the RFI:

DC Components, Equipment, End-Use Devices, and Technologies

1. What DC components and equipment are needed to enable more efficient integration of DC devices with other DC devices? What is the current technology readiness level (TRL) of these devices? What specific research is needed to advance the TRL (e.g., design work, laboratory testing, pilot and/or commercial demonstration)?
    - Advances in power electronics provide the opportunity to readily control DC voltage levels. This includes requirements for development of solid-state transformers.
    - For mobility applications (e.g., rail, EVSE, V2G, etc.), reliable and safe DC Contactors forming the BDU (Battery Disconnect Unit) are necessary to isolate the high-voltage battery from the high-voltage network along with all the electrical components of the vehicle in the event of danger. They are required to reliably disconnect in case of failure and therefore ensure galvanic isolation between the battery and the rest of the vehicle's electrical system. Such devices (which can carry 500A continuously) already exist and are in use (hence TRL #9). For example, refer to companies such as: https://www.schaltbau.com/en/
    - For large power applications (e.g., in HV substations), AC/DC converters, along with AC/DC/AC power transfer equipment, have been prototyped and some are installed and undergoing trials in the UK, TRL could be considered 5-6. This equipment utilizes advanced power electronic components using modern SiC semiconductor devices. This equipment is essentially self-contained and has its own protection and control functions in-built.

- Typical functionality provided includes the following:
  - Real power transfer between substations and to the other connected DC equipment (e.g., EVSE and V2G)
  - Reactive power support
  - Voltage support
  - Power factor correction and improvement
  - Phase imbalance improvement
  - Loss reduction
  - Harmonic content improvement (Difficult to detect due to low impedance at the GTIs terminals)
  - Fault ride through
  - Creation of a controlled DC micro network
- An example of such equipment could be that provided by: https://www.turbopowersystems.com/

2. What are the TRL, cost effectiveness, efficiency, and availability of the following technologies?
   Technology Readiness Levels (TRLs) are based on the definitions provided by NASA (https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf).
   a. DC-DC converters that provide high voltage and high current to enable high power transfer or bi-directional transfer between various DC equipment.
      - Technology Readiness Levels of high voltage direct current (HVDC) components have recently been evaluated by several organizations, including the European Union's Horizon 2020 Research and Innovation Program, Progress on Meshed HVDC Offshore Transmission Networks (PROMOTioN) project[1]. With large, interconnected generation systems, e.g., wind turbines and solar systems, often meshed systems are employed. These allow multiple power-flow paths between terminals.
      - DC-DC converters change voltage levels and are at an elevated level of maturity and technology readiness levels. Currently, these power electronic components are at TRL levels of 8 and above.
   b. Solid-state transformers for integration of renewables, electric vehicles (EV), and energy storage.
      - The solid-state transformer (SST), which comprises state of the art power electronics with galvanic isolation to interconnect two separate alternating current (AC) or direct current (DC) power grids, is considered to be the dominant solution[2]. Several projects worldwide are developing SSTs and TRLs are now between 4 and 5.

[1] Wu, J., and Marshall, R., D12a Meshed HVDC Transmission Network Technology Readiness Level Review, European Union's Horizon 2020 research and innovation programme under grant agreement No 691714, PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks, 2020.
[2] Cervero, D., *et. al.,* Solid State Transformers: A Critical Review of Projects with Relevant Prototypes and Demonstrators, *Electronics*, 2023, 12(4), 931; https://www.mdpi.com/2079-9292/12/4/931

- The European Commission Future Unified DC Railway Electrification System (FUNDRES) Project[3] relates to a proposed advanced railway electrification system using medium voltage DC grids, supported by renewable energy sources, and the use of train braking energy to move recovered energy into the grid. The proposed SST is designed to operate at 1,800 volts DC with rated power equal to 300 kW.
- Need for modular design techniques to compete with transformers on cost / flexibility (TRL = 4).

c. DC revenue-grade meters to measure, collect, and store real-time data for DC power systems.
    - We understand that IEC 62053-41 is currently under discussion to provide an international standard for dc static meters for active energy with accuracy classes of 0.5% and 1%. The standard will detail a range of nominal voltages, currents and sets limits on the maximum power consumption of the voltage and current channels of the meter. However, at the current time, our understanding remains that there is no approved DC revenue-grade meter for use within the UK. Discussions with, for example, Elexon, could be instigated to verify current progress through developing a standard and its scheduled roll-out.
    - In Europe, there are approved revenue-grade DC meters. For example, LEM manufacture a range of meters, known as DCBM which have successfully undergone type testing against German regulations. These DC meters are therefore permitted to be used for billing in Germany.
    - We would recommend undertaking an internal marker assessment to understand the extent to which DC metering systems have been developed, approved for use, certified, and implemented.

d. DC power systems for buildings that can be directly coupled with distributed energy resources (DERs) to reduce energy losses with fewer redundant stages of power conversions.
    - Currently most large building energy consumers (HVAC, Lifts/Escalators/ IT) use DC as intermediate or final link from 1000V dc to 24V dc. No standards have been established for DC distribution. Other industries Rail, Marine, Automotive have used DC 1000Vdc, 110Vdc, 24Vdc, 12Vdc, whereas it was displaced from the domestic/buildings environment due to the ease of transmission of (High) AC voltages.
    - Standardized ratings of the DC network [TRL 2]

e. DC-based end-use equipment (e.g., refrigeration, cooktops, lighting, motor-driven loads) that can be integrated into an efficient DC-based power system.
    - Most equipment has an AC/DC or AC/DC/AC converter to allow the supply and control of loads a direct DC/DC or DC/AC would be possible with standardized voltages, as well as continuing to accept AC. [TRL5]

[3] Future Unified DC Railway Electrification System (FUNDRES) Project, Fact Sheet H2020, CORDIS, European Commission. Available online: https://cordis.europa.eu/project/id/881772

- An increasing fraction of residential end-use loads operates on direct current (DC), allowing the direct use of DC from onsite DC sources (Photovoltaics, battery storage), thus avoiding the energy losses from converting DC power to alternating current (AC) and back to DC[4].
- DC appliances are typically more efficient than their AC counterparts. However, interoperability and safety research are needed.
- Local energy storage systems offer the potential to stabilize the grid, offer emergency power back-up, and higher efficiencies when coupled with photovoltaic and wind power systems. Development of acceptable standards for end-use equipment requires input from manufacturers and end-users.

DC Adoption Pathways and Use Cases

3. What are the most likely commercial applications for DC-based power systems in the short (3-5 years) and long terms (5+ years)?
    - Any complex that has significant renewables connected (e.g., solar, wind, batteries, etc.)
    - Systems with significant levels of energy recovery, for example, rail, cranes, road vehicles.
    - Microgrids (from small developments such as military bases/hospitals through to entire town/cities)
4. What are the recommended ideal locations (e.g., where on the distribution grid, geographically, or at particular facility types like electric vehicle supply equipment stations) to deploy DC-based power related demonstrations and what technology(ies) would ideally be demonstrated?
    - In addition to its in-house testing capabilities, Ricardo recommends the high voltage and power electronics test facilities at the Ohio State University, Mississippi State University, and Florida State University. The National Renewable Energy Laboratory also has facilities for evaluating advanced power electronics and electric machines.
    - There are several dedicated test centers in the UK which could be used for prototyping innovative DC based networks, their interconnectivity, protection, control, and metering, etc. One such center is known as the "Power Networks Demonstration Centre," please refer to the following website: https://pndc.co.uk/
5. What kind of buildings/facilities are the best fit for early DC-based implementation and why?
    - New builds would be most appropriate so that the equipment, cabling, and systems can be designed and installed without the challenges posed by retrofit systems.
    - Industrial, commercial, and residential buildings can all benefit from the higher efficiencies of DC equipment and appliances. Research is recommended regarding specific economic benefits, including total cost of ownership comparisons as well as impacts on the electrical grid (energy storage at utility scale and behind the meter, infrastructure costs, time scales).

[4] Vossos, V., *et. al.,* DC Appliances and DC Power Distribution, A Bridge to Future Net-Zero Energy Homes, Lawrence Berkeley National Laboratory, September 2017.

6. What are potential DC adoption pathways for residential and commercial buildings, and how could we structure a solicitation to best inform that transition to greater adoption?
    - There are several there are several technological and market barriers impeding the development of DC distribution, which have kept this technology at the demonstration phase[5].
    - Key barriers requiring additional research include:
        - The existing electricity generation and transmission system is based on AC, requiring a significant development effort to convert to DC. Research on the overall cost, time requirements, security, safety, and time requirements is required.
        - End-use systems (buildings, equipment, appliances) are supplied with AC power, requiring a conversion to DC for all loads when local DC generation (e.g., PV, storage) is not available.
        - Because DC systems are in the demonstration phase, there are relatively small numbers of suppliers for DC-ready equipment and converters.
        - Training of technicians, designers, and developers of DC system will require considerable time and resources.
        - Equipment, infrastructure, metering, and control systems must be designed to address safety, grounding, and fault protection.
        - Currently, there are gaps in selection of key technologies and establishment of standards.

7. What research is required to directly connect an EV via a DC bus to a residential/commercial building allowing for a more flexible and efficient bi-directional power flow? What components/equipment and research are required to accelerate the adoption of DC bi-directional power flow equipment in residential/commercial buildings and improve the overall system efficiency?
    - Building Distribution Voltages standardization, develop power distribution topologies and protection Technology transfer from Rail/Marine to Buildings [TRL 2]
    - Establish application requirements and opportunities, mobile devices USB-C, LED lighting, monitors and displays.
    - Market assessment of Standardized connectors/switches and protection devices identification of critical gaps.
    - Availability of Solutions for accurate distributed metering
    - Interaction of DC / AC system need for immunization /protection of AC transformers.

8. What are the research opportunities to demonstrate DC building blocks for a local DC microgrid that increase the overall system efficiency and reliability when compared to a similar alternating current (AC) system?
    - Optimizing of DC architecture for maximum efficiency and availability, bi-polar supply and facility to parallel for higher loads.

[5] Vossos, V., *et. al.*, Adoption Pathways for DC Power Distribution in Buildings, *Energies*, Vol. 15, 786, 2022.

- Integration of AC / DC Distribution systems
- Conduct efficiency and cost advantages (capital and operations costs) for DC vs. AC systems.
- Develop safety and protection standards.
- Conduct research on power quality issues in DC versus AC/

Near-Term (3-5 Years) Opportunities

9. What are the high priority DC-related technologies and/or research needs to successfully integrate or transition to DC-based power distribution networks?
    - Improved detection methods and design tools to address DC arc flash. Currently, the best approach is to remain outside the arc flash boundary, but this can lead to packaging and efficiency issues.
    - A roadmap is required to identify sequence of product development; what baseline components are required to allow development of key DC system elements?
10. What specific DC equipment (e.g., DC-DC converters) and components are required to serve as an enabling device for the integration of DERs with a microgrid or DC-related infrastructure?
    - Modular DC-DC "Transformers" for standardized voltage and current ratings
    - Development of standardized control systems and component interoperability.
    a. What are the research opportunities to advance the TRL to simplify the interconnection of microgrids to the grid in one package using only DC-DC related components and equipment and eliminating DC-to-AC followed by AC-to-DC conversion?
        - Define optimum DC Bus low voltage per application.
        - Use of existing technology
        - Establishment of standardized distribution system voltages.
    b. What additional research is required to maintain the quality and reliability of DCDC converters while minimizing unnecessary costs and improving the efficiency of the converters?
        - Minimizing losses in switching topologies to reduce thermal duty and protecting from switching transients to reduce dielectric degradation.
        - Development of DC plugs and sockets.
11. What advancements are required in power electronics to enable DC and mixed DC/AC microgrid topologies that can reduce power conversion, increase efficiency, and improve reliability?
    - Ultra-low loss switching
    - Grid interface systems and standards.
12. What power electronics need to be advanced and demonstrated to provide reliability and stability to DC systems?
    - DC Network stability of multiple DC/DC or DC/AC converters connected in parallel to a common DC bus.
    - Associated control systems and communications.
13. What are the enabling or emerging technologies that can:
    a. Advance adoption pathways for DC power in buildings?

- LED Lighting
- IT/Mobile devices adopting a common USB-C power input.
- Voltage standards

b. Accelerate DC-based power distribution networks for efficient DC-DC integration of DERs?
    - Build upon DC systems currently in operation: electronics, lighting, HVAC, water heating, driers, pumps, fans, EVSE.

c. Enable residential/commercial buildings to better serve as DC building blocks for local DC microgrids?
    - Capability for energy storage

14. What are the opportunities for EVs to directly support a residential/commercial building directly via a DC bus that eliminates the requirement of an inverter and increases system efficiency and reliability?
    - Through battery energy storage: HVAC equipment, lighting.
    - Direct: communications

Longer-Term (5+ Years) Opportunities

15. What are the opportunities for standardizing DC voltages and system design across various DERs, end uses, and DC plug-in electric vehicle chargers? How can research help to accelerate this process?
    - Industry organizations (e.g., SAE, IEEE) awareness workshops.
    - Manufacturer surveys.
16. What areas of research are required to potentially accelerate adoption of DC buildings and related technologies by residential and commercial developers and customers?
    - A sizable portion of microgrids and EV charging stations are networked and allow online access, introducing many potential network threats, such as Electricity Theft, Identity Theft and False Data Injection, etc. Cybersecurity issues require additional research to identify threats and to evaluate mitigation methods.
    - Anomaly detection models should be developed utilizing machine learning and AI methods to address security threats and identify threat sources.
17. What pertinent data (e.g., performance and cost) are required to accelerate large-scale commercialization and deployment of DC-based end-use equipment?
    - Techno-economic models of DC power distribution systems for distribution level, industrial, commercial, and residential applications should be developed (or, in some cases upgraded) to quantify potential savings, support development of an implementation roadmap, define future market scenarios. Ricardo has considerable experience in developing these types of models, including garnering support and input from industry representatives.
    - Interoperability of components and systems.
18. What current or upcoming communication standards or protocols should be demonstrated and/or developed to ensure successful DC-DC integration and interoperability?

- IEEE Standard 2847-2021 has been developed to define physical layer and data link layer specifications for power supply and communications over power lines from a DC power source to multiple DC loads.
- Compatibility with US DOE EERE Strategic Plan for Implementing Framework to reduce energy consumption per square foot in all U.S. buildings by 30% prior to 2030.

19. What specific codes and standards will the deployment of a DC-based power system help inform?
    - There are a few building codes and standards that address DC systems., including NFPA 70 (U.S. National Electrical Code). The National Electrical Manufacturers Association indicates that 64% of their members indicated the DC market has standardization gaps and another 30% indicated the market is not mature enough for standards development[6]
    - Existing standardization gaps include:
        A. Connectors, wiring, interfaces, bidirectional vehicle charging / discharging systems.
        B. Electronic circuit protection
        C. DC data center at 380 VDC
        D. DC HVA/C standards at 24/380 VDC
        E. DC lighting standards at 48/380 VDC
        F. Safety testing and test methodologies
        G. Energy efficiency standards such as EnergyStar for DC equipment
        H. National Electrical Code (NEC) should update and equipment rating standards to require both AC and DC ratings.
        I. Integration of appliances and equipment for DC into existing AC infrastructure
        J. Role of USB
        K. Interconnections

Safety and Protection

20. What power electronic solutions are needed and required to enhance the safety of a DC microgrid?
    - Improved rapid shutdown procedures to prevent electrical shock and protect first responders. NFPA 70E (Electrical Workplace Safety) designates systems greater than 50 volts DC as hazardous.
    - Development of improved arc fault circuit interrupters (AFCIs) and ground fault circuit interrupters (GFCIs) and other protection components.
    - Improved risk assessment procedures (as referenced by NFPA), including full definition of high voltage direct current (HVDC) systems.
    - Development of arc-resistant power electronics components.
    - Define and address battery system hazards such as shock, fire, arc flash, and thermal runaway.

[6] National Electrical Manufacturers Association, Direct Current in Buildings, NEMA DO 1-2018.

21. What protection equipment is needed to interface with a DC/AC microgrid that will enable the reliable operation of the microgrid during disaster events?
    - General protection aspects covering topics such as those summarized below will need to be considered:
        - Sensitivity and clearance
        - Speed
        - Protection overlap.
        - Discrimination
        - Ability to reclose.
    - The ability to ensure the safe discharge from DC cables and the power electronic (AC/DC) devices must be assessed (the equipment and cables may retain stored energy following de-energization).
    - Consider facility for all infeed's and isolators to be open, locked and cautioned.
    - Consider requirement and facilities for earthing the system (substation and/or zone of work)
    - Appropriate operational procedures, documentation and safety systems will need to be introduced. Training for personnel will be crucial.
    - Determine how to identify DC cables amongst neighboring cables.
    - Consider process for proving resistance or impedance between the energized conductor and the neutral or ground at the site of work.
    - Review risk of induced voltage from adjacent circuits

22. What are the opportunities to advance DC components/equipment to improve the protection and coordination and increase the resiliency and interoperability of multiple connected Distributed Energy Systems (DERs)?
    - Ricardo suggests consulting with an approved test house/demonstration center such as Underwriters Laboratory of the UK's PNDC.
23. For DC-DC converters, what are the safety mechanisms (e.g., NFPA 79) that are required in manufacturing, and how can research help address issues related to fire protection, health, and safety?
    - IEC 60950-1 (up to 600 volts)
    - Europe's EN 60950-1 and UL/CSA 60950-1 that apply in the US and Canada
    - AS/NZS 60950-1 that serve Australia and New Zealand.
    - Application- and product-related standards such as ETS 300 132-2 "Power supply interface at the input to telecommunications equipment"
    - IEEE 802.3af "DTE Power via MDI" for Power-over-Ethernet (PoE) may also apply for some equipment, but these standards reference IEC 60950-1 for any relevant safety-related aspects[7].

[7] Flex, Inc., Technical Paper 018, Safety Requirements for Board-Mounted DC/DC Converters, 31/28701-FCB 101 378 UEN Rev B, 2017.

24. What emerging technologies can be demonstrated to reduce the safety and electric shock risks associated with higher DC voltage operations?
    - With regards LVDC systems, tests at the UK PNDC have taken place to demonstrate a new protection algorithm to protect the last-mile connection for a DC cabled system. They could be consulted to understand latest developments.
    - Other emerging safety technologies for HVDC include equipotential bonding (electrically connecting all exposed conductive equipment/wires with the same voltage), emergency stops (based on overheating sensors), high-voltage interlocking loops (HVIL: uses a low-voltage loop to monitor the integrity of the high voltage circuit), and isolation monitoring circuits.
25. What further research and/or analyses are required to ensure DC components/equipment protection is developed and proper guidelines are established?

- In general, DC systems present significant safety and protection challenges. DC faults are more difficult to detect and clear. Their associated arcs are more aggressive than in AC, and they require longer time to be cleared. This makes the risk of fire in DC systems higher than in AC. In addition, the residual current devices (RCDs) which are commonly used in AC systems to protect against electric shocks and fire are not commercially available for DC systems.
- For LVDC, there is the IEC technical committee/working group (SEG4) which is investigating LVDC safety aspects. They could be consulted.
- For large power transfer devices (AC/DC), it is typical that the AC-DC power electronics converters have poor short circuit fault capability and can trip for remote faults. This can lead to substandard protection selectivity and unnecessary disconnection of larger part of the system. Such issues increase the need for fast and reliable DC protection solutions that reduce the risk and the cost of operating such systems. All such issues should be investigated.

EPIC Program Area and Funding

26. For each suggested area of research above, what are the initial and concluding TRLs of the technologies being recommended? What is required to advance each technology's market readiness?
    - Based upon the current state-of-the-technology for DC-based power systems, a significant need exists for understanding the political, economic, societal, technical, environmental, and legal (PESTEL) issues in moving forward with replacement of AC systems or removing inverters from transportation and electrical distribution and end-use equipment. As noted, TELs for the DC components range from 3 to 8, with those at level 8 representative of existing AC systems with DC subcomponents.
    - Because this is a developing area that will impact the entire electrical industry, a roadmap is required to ensure that key stakeholders have been identified, risk assessments (for all PESTAL categories) have been completed, robust economic models have been developed and assessed, and a realistic associated timeline has been developed. Ricardo has considerable experience in conducting these detailed product and market assessments and has expertise in all impacted areas, including market analyses, environmental impacts, financial modeling, risk assessment, product planning, electrical and control

systems, power electronics, renewable energy, efficiency calculations, as well as codes, standards, regulations, and recommended practices.

27. For each suggested area of research above, what is the recommended CEC funding amount? What percentage of the funds should be provided by the recipient in terms of match?
    - Because DC power systems and components are at the development, pilot deployment, and demonstration phases, and the market is not mature, most organizations involved in research, development, and product demonstrations will require significant grant funding to justify moving forward in the face of an unknown market.
    - It is expected that grant recipients would be expected to provide relatively low levels of matching funds for this research (0% to 20%).

Ricardo is pleased that CEC is considering grant support for research on the topic of DC-based electrical power systems. Ricardo's response to the RFI is intended to help define critical research requirements for this critical topic and to provide an indication that we are ready to work with CEC Staff to further develop the proposed concepts.

Respectfully,

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