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Cost-Effective and Energy-Efficient Megawatt Medium-Voltage Power Conversion Using Loosely Coupled Resonant SST for AI Centers

Additional submitted attachment is included below.

Electric Program Investment Charge 2026–2030 (EPIC 5)

Research Concept Proposal Form

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1. **Please provide a brief description of the proposed concept that you would like the CEC to consider as part of the EPIC 5 Investment Plan. What is the purpose of the concept, and what would it seek to do? Why are EPIC funds needed to support the concept?**

Project Title: Cost-Effective and Energy-Efficient Megawatt Medium-Voltage Power Conversion Using Loosely Coupled Resonant Solid-State Transformer (LCR-SST) for AI Data Centers and EV Fast Charging Stations

AI data centers are projected to consume hundreds of terawatt-hours annually by 2035, demanding power conversion technologies that are not only energy-efficient but also cost-effective, scalable, and reliable. It is estimated that the global market for power supplies, distribution, and management systems serving AI data centers and cloud computing is expected to reach approximately USD 145–150 billion. Conventional line-frequency transformers and multi-stage AC-DC architectures suffer from low efficiency, bulkiness, high cost, low reliability[1], and limited dynamic response. To support the rapid growth of AI workloads and comply with emerging energy and environmental standards, innovative power electronics solutions are urgently needed.

This proposed area of interest explores the development of a novel megawatt-scale, medium-voltage (MV) power conversion system based on a Loosely Coupled Resonant Solid-State Transformer (LCR-SST) architecture. The approach aims to reduce energy loss, footprint, and cost while enabling flexible, modular deployment, and achieve more reliable operation in large-scale AI data centers. The technologies developed in this area

[1] According to a 2023 survey by the authoritative organization Uptime Institute, power supply failures (accounting for 52%) are the leading cause of data center outages.

can also be easily expanded to EV fast charge stations, large-scale MWh energy storage systems, and other industry applications.

Based on our preliminary study, the overall system efficiency of the proposed LCR-SST will exceed 98% comparing to the conventional systems at 95% and conventional SST at 97%. Additionally, the total cost of the system is anticipated to be at least 30% lower than conventional systems and 15% lower than that of conventional SST. As much as 50% savings in iron and copper materials are expected. Reliability will be considerably improved over the existing technology. The proposed technology can be commercialized and implemented in data centers, fast-charging stations, utility-scale energy storage systems, and other industry applications within 3 to 5 years.

Objectives:

- Develop high-efficiency (>98%), high-power-density MV LCR-SST (exceeding 100kW/L) suitable for AI data centers and other applications, EV fast charging stations, and utility-scale energy storage systems, using the loosely coupled resonant topology.
- Minimize total cost of ownership (TCO) through modular and scalable design.
- Enhance power quality (<1% THD and unit power factor), reliability, and resilience through advanced control and protection.
- Validate performance against industry benchmarks in a lab-scale and pilot deployment.

Technical Approach:

- Topology: A loosely coupled resonant link enables soft-switching and high-frequency operation, increases isolation voltage, improves efficiency and reduces magnetic component size.
- MV Front-End: Utilize SiC-based MV multilevel AC-DC conversion to directly interface with utility MV distribution (e.g., 13.8 kV), eliminating the low frequency transformer, reducing transformation stages, reducing total harmonics distortion, increasing redundancy, enhance fault tolerance, and significantly reduce land use.
- Isolation and Conversion: Employ high-frequency, loosely coupled planar transformers and resonant topology using inductive wireless power transfer principle, to transfer power across galvanic isolation, reduce the burden of conventional high-frequency transformer in conventional SST. The proposed architecture will significantly improve insulation of the isolation transformer, hence, reducing system cost and increase reliability.
- DC Output Stage: Multi-port DC output for direct AI server/rack-level connection or integration with backup systems (e.g., batteries, supercapacitors).
- Control System: Hierarchical digital control, fault-tolerant architecture, and advanced thermal management for reliability and operational flexibility.

2. **In accordance with Senate Bill 96[i], please describe how the proposed concept will "lead to technological advancement and breakthroughs to overcome barriers that prevent the achievement of the state's statutory energy goals." For example, what technical and/or market barriers or customer pain points would the proposed concept address that would lead to increased adoption of clean energy technology or innovation? Where possible, please provide specific cost and performance targets that need to be met for increased industry and consumer acceptance. For scientific analysis and tools, provide more information on what data and information gaps the proposed concept would help fill, and which specific parties or end users would benefit from the results, and for what purpose(s)?**

The proposed technology directly supports California's statutory clean energy goals under Senate Bill 96 by addressing multiple technical and market barriers currently limiting the construction of new AI data centers, widespread deployment of EV fast-charging infrastructure, and adoption utility-scale energy storage.

Key Technical Breakthroughs and Barriers Addressed:

- **Elimination of Low-Frequency Transformers:**
  - AI-data centers and conventional fast-charging stations rely on bulky, heavy, and expensive low-frequency (LF) transformers for voltage conversion from medium-voltage (MV) distribution lines (~13.8kV) to 480V AC. These components significantly increase installation costs, system footprint, energy losses, and lead time (up to 28 months).
  - The proposed system eliminates the LF transformer by integrating a modular, multilevel LCR-SST structure with high-frequency isolation (50–100kHz), leading to 50–70% volume and weight reduction, and potentially 20–30% lower installation costs.
  - The unique loosely coupled transformer design takes advantage of wireless power transfer principle to separate the primary and secondary coils. This novel architecture design significantly simplifies packaging and enhances insulation and lowers parasitic capacitance between the primary and secondary coils as compared with the conventional SST. This approach makes it easy for modularization, from hundreds of kilowatts to tens of megawatts.
- **Higher System Efficiency:**
  - By replacing traditional transformer infrastructure with high-frequency LCR-SSTs and high-efficiency power converters, system efficiency is expected to exceed 98%, compared to ~95% in conventional systems; and 97% of existing SST systems.
  - Over the lifetime of the infrastructure, this improvement can translate to significant energy savings, lower initial investment and operational costs, and reduced greenhouse gas (GHG) emissions.

- **Direct Connection to the MV Grid:**
  - Directly interfacing the LCR-SST with 5kV–13.8kV distribution networks bypasses the need for substation-level conversion infrastructure, enabling scalable, decentralized deployment of AI data-center power supplies and EV fast-charging stations in urban, suburban, and even rural areas, and reducing land use.
  - This flexibility removes a major siting barrier for new AI centers and EV fast charge stations and reduces dependency on legacy infrastructure upgrades, thus accelerating deployment.
- **Support for Mult-Port Voltage Output:**
  - AI data centers require a range of DC and AC power to support servers, thermal management, lighting, photovoltaic systems, and energy storage. The technology can meet the diversified power demands minimum effort.
  - For EV charge stations, the proposed system outputs a flexible 400-1000VDC, natively supports both legacy EVs and new-generation high-voltage EVs, improving user accessibility and future-proofing the infrastructure. This dual compatibility is critical for customer satisfaction and broader EV adoption.

Market Barriers and Customer Pain Points Addressed:

- **High Capital Cost of Existing Technology**: LCR-SST-based designs reduce equipment and civil infrastructure costs by removing the need for large transformers and extensive concrete pads, and utility coordination. We estimate up to 30% cost reduction per installation can be realized.
- **Slow Permitting and Grid Interconnection Delays**: LCR-SSTs with standardized, modularized designs can be rapidly deployed and integrated, minimizing delays in permitting and inspection. This leads to faster time-to-market for new installations (6 months versus 28 months currently).
- **Grid Strain and Inflexibility**: When combined with on-site energy storage systems and PV, the high-frequency LCR-SST can be integrated with advanced grid support functions, such as reactive power control, voltage regulation, and bidirectional energy flow. These features reduce grid stress and support smart; distributed energy ecosystems aligned with SB 100 and SB 350 goals. For EV fast charge stations, V2G can be easily implemented without additional infrastructural cost.

Filling Data and Information Gaps:

Performance Modeling & Validation:

- The proposed concept will yield real-world data on LCR-SST-based charging station performance at MV levels, a domain where field-validated data is limited.

- This data will be essential for utilities (e.g., PG&E, SDG&E), OEMs, and regulatory agencies (e.g., CPUC, CEC) to develop interconnection standards and planning tools for high-frequency MV-connected charging systems.

Stakeholders & Beneficiaries:

- Utilities will benefit from improved grid flexibility and load balancing options.
- AI data centers will benefit from faster deployment and reduced operating costs.
- EV fleet operators and OEMs will gain access to faster, more cost-effective, and location-flexible charging.
- City planners and developers will be empowered to deploy EV infrastructure in space-constrained urban environments.
- Consumers will experience reduced charging costs and increased availability of stations, accelerating EV adoption.

3. **Please describe the anticipated outcomes if this research concept is successful, either fully or partially. For example, to what extent would the research reduce technology or ratepayer costs and/or increase performance to improve the overall value proposition of the technology? What is the potential of the innovation at scale? How will the innovation lead to ratepayer benefits in alignment with EPIC's guiding principles to improve safety,[ii] reliability,[iii] affordability,[iv] environmental sustainability,[v] and equity?[vi]**

If this research concept proves successful—either fully or partially—it is expected to significantly enhance the value proposition of AI data center infrastructure and EV fast-charging infrastructure, with widespread benefits for ratepayers and utilities. The primary anticipated outcomes include:

- **Increased System Efficiency:** By eliminating the traditional low-frequency transformer and adopting a modular, multilevel, LCR -SST architecture operating at high switching frequencies (e.g., 50–100 kHz), the overall power conversion efficiency is projected to exceed 98%. This is a significant improvement over the ~95% efficiency of conventional systems and 97% of other SST systems considering the systems are operating at megawatt levels. The efficiency improvement translates to lower energy losses, thereby improve thermal management, reduce operational costs, and improve system performance and reliability.
- **Lower Capital and Installation Costs:** Removing the bulky and expensive low-frequency transformer will reduce the overall physical footprint and material usage (iron and copper), leading to lower capital expenditures and easier installation in space-constrained diversified environments. This reduction in infrastructure cost can directly benefit utilities, operators, and ratepayers.

- **Increased Renewable Integration and Grid Flexibility:** LCR-SSTs offer inherent advantages in voltage regulation, reactive power control, and galvanic isolation. Their ability to directly connect to medium-voltage distribution lines (e.g., 5kV to 13.8kV) without step-down transformers improves system flexibility and scalability, while potentially enhancing grid stability and supporting distributed energy resource (DER) integration.
- **Enhanced Safety and Reliability:** The modular design increases redundancy and fault tolerance. In the event of a failure in one module, the system can continue operating with minimal interruption, thus improving overall reliability and safety—both key pillars of the EPIC guiding principles.
- **Improved Affordability and Equity:** By reducing both capital and operational costs, the innovation enables more cost-effective deployment of fast-charging stations, particularly in underserved or remote communities where cost has traditionally been a barrier.
- **Faster Deployment:** The proposed technology promotes fast AI-infrastructure deployment and broader EV adoption, and supports equitable access to clean energy.
- **Environmental Sustainability:** Higher system efficiency and material reduction contribute directly to environmental goals by decreasing energy consumption, greenhouse gas emissions, and raw material extraction.
- **Scalability and Commercialization Potential:** The proposed LCR-SST-based architecture is inherently modular, making it highly scalable from sub-megawatt installations to tens of megawatts high-power hubs. This makes it well-suited for large-scale deployment, ultimately supporting California's and national goals for clean energy and electrified transportation.

4. Describe what quantitative or qualitative metrics or indicators would be used to evaluate the impacts of the proposed research concept.

Quantitative Metrics

- **System Efficiency (%):** Compare the end-to-end efficiency of the proposed LCR-SST-based system (>98%) with conventional systems (~95%), and existing SST system (97%); measure individual efficiencies of the modular multilevel converters and high-frequency transformer stages.
- **System Cost ($):** Analyze the total bill of materials (BOM), including power electronics, magnetics, and protection circuitry; compare projected manufacturing costs with traditional systems; compare installation costs and other infrastructure costs including land use, permit, and environment assessment costs with traditional systems that use low-frequency transformers.

- **Power Density (kW/kg or kW/L):** Evaluate reduction in size and weight by comparing the power-to-weight and power-to-volume ratios and demonstrate compactness due to the elimination of bulky low-frequency transformers.
- **Material Savings (%):** Quantify reductions in **iron** and **copper** used in the system, especially in the transformer stages; present environmental and resource benefits.
- **Voltage and Current THD (%):** Measure total harmonic distortion (THD) at the input and output terminals to validate grid compatibility and power quality.
- **Thermal Performance (°C rise):** Monitor temperature profiles and cooling requirements of LCR-SST-based systems versus conventional systems.

Qualitative Metrics:

- **Grid Integration Flexibility:** Validate the ability to connect directly to 5kV ~ 13.8kV distribution lines without additional transformer infrastructure.
- **Modularity and Scalability:** Evaluate the ease of scaling the system up or down based on power requirements and future standards.
- **Reliability and Fault Tolerance:** Evaluate how the modular structure improves fault isolation, system uptime, and maintainability.
- **Compliance with Standards:** Assess readiness for certification and conformance with UL, IEEE, IEC, or DOE fast-charging standards.
- **Environmental Impact:** Highlight the ecological advantages due to reduced raw material usage and improved energy efficiency.
- **Market Adoption Potential:** Evaluate ease of integration into existing infrastructure and cost-effectiveness from a utility, AI operators, or EV charging provider's perspective.

These metrics shall be gathered through a combination of simulation results, experimental data, prototype testing, and pilot site data. The final assessment will inform recommendations for future deployment at scale.

5. Please provide references to any information provided in the form that supports the research concept's merits. This can include references to cost targets, technical potential, market barriers, equity benefits, etc.

The proposed LCR-SST-based concept is supported by a range of recent academic and industry publications, government reports, and technology assessments. Key references that validate its technical and economic potential include:

- **DOE and ARPA-E Reports**: The U.S. Department of Energy and ARPA-E have identified solid-state transformers and medium-voltage fast chargers as a high-impact area for modernizing EV infrastructure. Specifically, ARPA-E's "Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely (BREAKERS)" and "Powering the Electric Grid through High Efficiency Solid-State Transformers"

programs highlight the need for compact, efficient, and grid-friendly charging solutions.
(Source: https://arpa-e.energy.gov/technologies/programs/breakers)

- **DOE Report**. The U.S. Department of Energy's *Advanced Power Electronics Roadmap* identifies SSTs as a transformative technology for achieving compact, efficient, and flexible grid-interfacing solutions [DOE, 2020].

- **NREL Report**. According to *NREL's Distributed Generation Renewable Energy Estimate of Costs* report, SSTs and modular power conversion systems are projected to reduce the size and installation cost of distributed energy systems by up to **30%** by 2030 [NREL, 2021].

- **IEEE Publications**. Research shows that SSTs enable better power quality, fault isolation, and voltage regulation at the distribution level, making them ideal for supporting bidirectional power flows from solar and storage systems [IEEE TPEL, 2019; APEC Proceedings, 2020].

- **IEEE Journals and Conferences**: Multiple papers published in IEEE Transactions on Power Electronics and other journals/conferences demonstrate that modular multilevel converters with high-frequency isolation and LCR-SST can achieve >98% efficiency, smaller volume, and lower material costs compared to conventional 60Hz systems.

  Source: M. Yao, R. Burgos, et al., "Medium-Voltage Solid-State Transformer Technologies for Future Smart Grids," IEEE TPEL, 2020;

  J. Lee, D. -U. Kim, S. Kim and S. -H. Lee, "Design and Validation of a 100 kW, 60 kHz, High Efficiency, Loosely-Coupled-Resonant Dual-Active-Bridge Converter," in IEEE Transactions on Industrial Electronics, vol. 72, no. 2, pp. 1501-1511, Feb. 2025;

  J. Lee, J. Roh, M. Y. Kim, S. -H. Baek, S. Kim and S. -H. Lee, "A Novel Solid-State Transformer With Loosely Coupled Resonant Dual-Active-Bridge Converters," in IEEE Transactions on Industry Applications, vol. 58, no. 1, pp. 709-719, Jan.-Feb. 2022

- **EPRI Studies**: The Electric Power Research Institute (EPRI) has evaluated the cost and operational barriers of existing EV fast-charging infrastructure and identified medium-voltage direct-connect chargers to reduce installation cost and eliminate bulky transformers.

  Source: EPRI Report 3002019276, "DC Fast Charging: Infrastructure and Grid Integration Considerations," 2021)

- **NREL and DOE EV Grid Integration Reports**: The National Renewable Energy Laboratory (NREL) provides cost and market analysis for EV infrastructure, suggesting that transformer-less, modular DC fast charging can significantly reduce station footprint and total cost of ownership (TCO).

  Source: https://www.nrel.gov/docs/fy22osti/80658.pdf)

- **Cost Targets and Market Trends**: The California Energy Commission and NYSERDA have both published cost targets for DC fast-charging installations, noting that a significant portion of cost comes from electrical infrastructure (up to 40%). Eliminating the low-frequency transformer addresses this directly and supports equity goals by enabling wider deployment in rural or disadvantaged communities with space or budget constraints.

  (Source: CEC "DC Fast Charging Cost Assessment," 2021; NYSERDA EVSE Make-Ready Program)

- **Market Barriers**. A key market barrier to DER integration is the lack of flexible, multi-port interfaces that support coordination between grid supply, renewable generation, storage, and loads. The proposed energy router with SST addresses this challenge directly. Conventional low-frequency transformers are bulky, difficult to site in urban areas, and inefficient at handling bidirectional power flow—barriers that SSTs overcome [IEEE Access, 2020].

- **Equity and Community Needs**. SST-based systems can enable localized energy resilience, especially in disadvantaged communities prone to grid outages or with high energy burdens. By supporting PV and storage integration, they can reduce reliance on centralized infrastructure and improve local energy access [CEC EPIC Equity Framework, 2022].

- **LBNL Report**. Modular SST-based routers can be deployed closer to the point of use, enabling community-level control and potentially supporting microgrids in areas with limited grid investment [Lawrence Berkeley National Laboratory, Grid Integration Report, 2020].

- **California Policy Alignment**. The proposed technology aligns with California's *SB 100* goals for 100% clean energy, by enabling high-penetration DER integration. The technology also supports *CEC's Electric Program Investment Charge (EPIC)* objectives for grid decarbonization, reliability, and ratepayer benefits through innovation.

6. The EPIC 5 Investment Plan must support at least one of five Strategic Goals:[vii]

a. Transportation Electrification

When applied to EV fast charge stations, the proposed technology directly supports transportation electrification.

b. Distributed Energy Resource Integration

The proposed technology directly supports the use of distributed energy resources by integrating solar and energy storage with the LCR-SST systems.

c. Building Decarbonization

The proposed technology, when applied in data centers, directly supports the building decarbonization of data center buildings.

d. Achieving 100 Percent Net-Zero Carbon Emissions and the Coordinated Role of Gas

The proposed technology works seamlessly with renewable energy integration and energy storage systems, hence, pave the way for achieving 100% net-zero carbon emissions.

e. Climate Adaptation

The proposed technology works seamlessly with renewable energy integration and energy storage systems, hence, pave the way for climate adaptation.

7. Additional Information:

It is worth to note that, currently, Asia Pacific, especially China, leads in terms of market share and rapid growth due to significant investments in smart grids, urbanization, and industrialization in countries like China, India, and Japan. Europe (with Germany as a major contributor) is also showing strong growth, fueled by aggressive renewable energy targets, smart grid initiatives, and the presence of leading manufacturers like Siemens and Alstom. In the meantime, even though the U.S. is strong in research and innovation in SST, there is a lack of coherent effort in the commercialization of SST, significant hinder the technological advancements and investments in grid modernization and renewable energy integration.

According to Fortune Business Insight[2], The global solid state transformer market size was valued at USD 123.2 million in 2023 and is projected to be worth USD 303.3 million by 2032. Most of SST-based commercial products are manufactured outside of the US (mostly in China) and imported by US companies. The proposed area of interest not only supports US manufacturing but also promote further develop of LCR-SST technology which is the next generation SST that supports lower cost, higher efficiency, and improved reliability.

Finally, megawatt SST development and commercialization is a significant effort, demanding large amounts resources, funding, and collaboration. It is not possible for private enterprises to demonstrate and commercialize this technology without government funding support. We anticipate the development of LCR-SST from current TRL-4 to TRL-8 and ultimate large-scale commercialization will need a support level beyond $30 million.

[2] https://www.fortunebusinessinsights.com/solid-state-transformer-market-106374

i See section (a) (1) of Public Resources Code 25711.5 at: https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=PRC&sectionNum=25711.5.

ii EPIC innovations should improve the safety of operation of California's electric system in the face of climate change, wildfire, and emerging challenges.

iii EPIC innovations should increase the reliability of California's electric system while continuing to decarbonize California's electric power supply.

iv EPIC innovations should fund electric sector technologies and approaches that lower California electric rates and ratepayer costs and help enable the equitable adoption of clean energy technologies.

v EPIC innovations should continue to reduce greenhouse house gas emissions, criteria pollutant emissions, and the overall environmental impacts of California's electric system, including land and water use.

vi EPIC innovations should increasingly support, benefit, and engage disadvantaged vulnerable California communities (DVC). (D.20-08-046, Ordering Paragraph 1.) DVCs consist of communities in the 25 percent highest scoring census tracts according to the most recent version of the California Communities Environmental Health Screening Tool (CalEnviroScreen), as well as all California tribal lands, census tracts with median household incomes less than 60 percent of state median income, and census tracts that score in the highest 5 percent of Pollution Burden within CalEnviroScreen, but do not receive an overall CalEnviroScreen score due to unreliable public health and socioeconomic data.

vii In 2024 the CPUC adopted five Strategic Goals to guide development of the EPIC 5 Investment Plan. A description of the goals can be seen in Appendix A of CPUC Decision 24-03-007 available at: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M527/K228/527228647.PDF