Executive Summary

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1. **Title of the Project: Solid State Transformer Technology for Emerging Trends in Electric Mobility and DC Micro-grid**

2. **Date of Start of the Project: 01/10/2021.**

3. **Aims and Objectives**:
   - Pioneer research work towards adoption of Solid-State Transformer technology with specific reference to Wide Band Gap (WBG) semiconductor technology and HighFrequency Magnetics for enhanced efficiency and improved reliability.
   - Development of Solid-State Transformer working prototype employing DC interface port for charging of electric vehicles.
   - Design of bi-directional, isolated, and soft-switched converter for automotive and traction applications to promote e-mobility to replace conventional, non-isolated and hard-switched counterparts.
   - Development of resilient industrial DC back-up system for critical loads in industry and DC Micro-grid environment.
   - Technology transfer to industry / setting up pilot scale charging station for electric vehicles.

4. **Significant achievements (not more than 500 words to include list of patents, publications, prototype, deployment etc)**

In this project, the following key research findings have been established:

Fault-Tolerant, Soft-Switched DC-DC Converter for SST Applications: Developed a topology (as shown in Fig. 1) for Solid-State Transformer (SST) applications. Incorporated a Voltage Restorer Rectifier to handle switch open/short circuit faults, ensuring a smooth and reliable transition between pre-fault and post-fault operation.

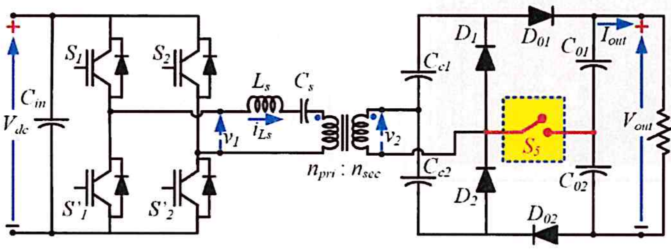

Fig. 1 Schematic of Fault resilient DC-DC converter with reconfigurable Voltage Restorer Rectifier

Fig. 2 Actual photograph of 1.25 kW hardware

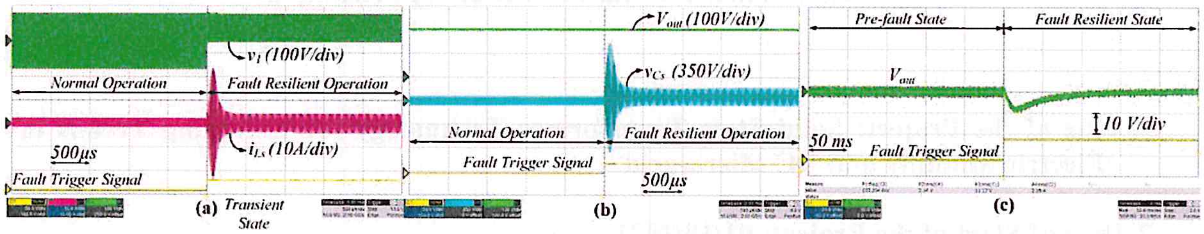

Fig. 3. Experimental waveforms for switch S'_2 short-circuit to demonstrate fault resilient operation: (a) Resonant current (i_{Ls}) and input tank voltage (v_1). (b) Output voltage and resonant capacitor voltage (v_{Cs}). (c) Output voltage transient during fault resilient operation and fault trigger signal.

overall converter gains without requiring a high transformer turns ratio. This design also reduces the equivalent AC resistance, resulting in a minimized value of resonant inductance for the design frequency and quality factor.

Design Specifications:

- **Input Voltage**: 230 V AC or 325 V DC.
- **Battery Charging Current**: Maximum 15 A.
- **Battery Charging Voltage**: Maximum 54 V.
- **Operating Frequency**: 40 kHz.
- **Key Components**: High-frequency transformer, energy transfer inductor, and DC-link capacitors.

One dual active bridge (DAB) based Electrical Vehicle (EV) charger have been also developed under this project targeting electrical mobility / Electrical Vehicle as a pioneer application by utilizing key features of energy efficient, bidirectional DC-DC converter as shown in Fig.4. The system incorporates a high-frequency transformer and offers bidirectional power flow between two DC buses.

Fig 4: SST based EV charger

The DAB converter circuit as shown in Fig. 5, comprises two identical full bridges-primary and secondary-connected via a high-frequency transformer and an energy transfer inductor. Such practical topology allows for high efficiency and bidirectional power flow. The converter's power flow is managed using phase-shift modulation, which adjusts the phase between the primary and secondary bridges to control energy transfer.

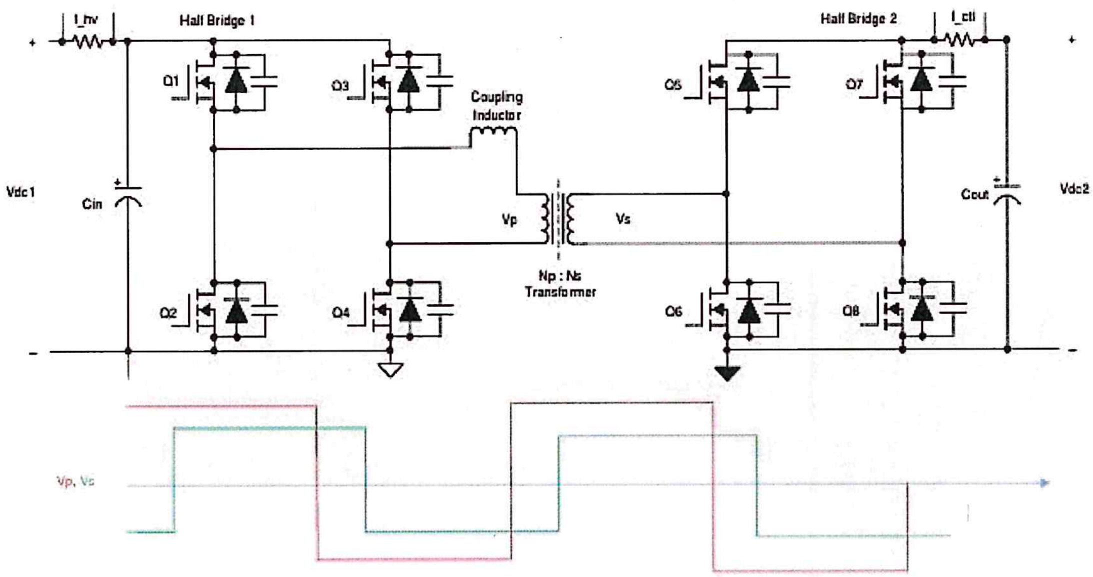

Fig. 5: Circuit diagram dual active bridge

Circuit board details:

The protection board in Fig. 6 has designed to monitor key electrical parameters, including DC current (I_{dc}), DC voltage (V_{dc}), output current (I_{out}), output voltage (V_{out}), and inductor current (I_L), utilizing the TL082 operational amplifier. This board also plays a crucial role in transmitting pulses from the Pulse Width Modulation (PWM) test point to the 316J driver board, ensuring proper control and communication between the power management and protection circuits.

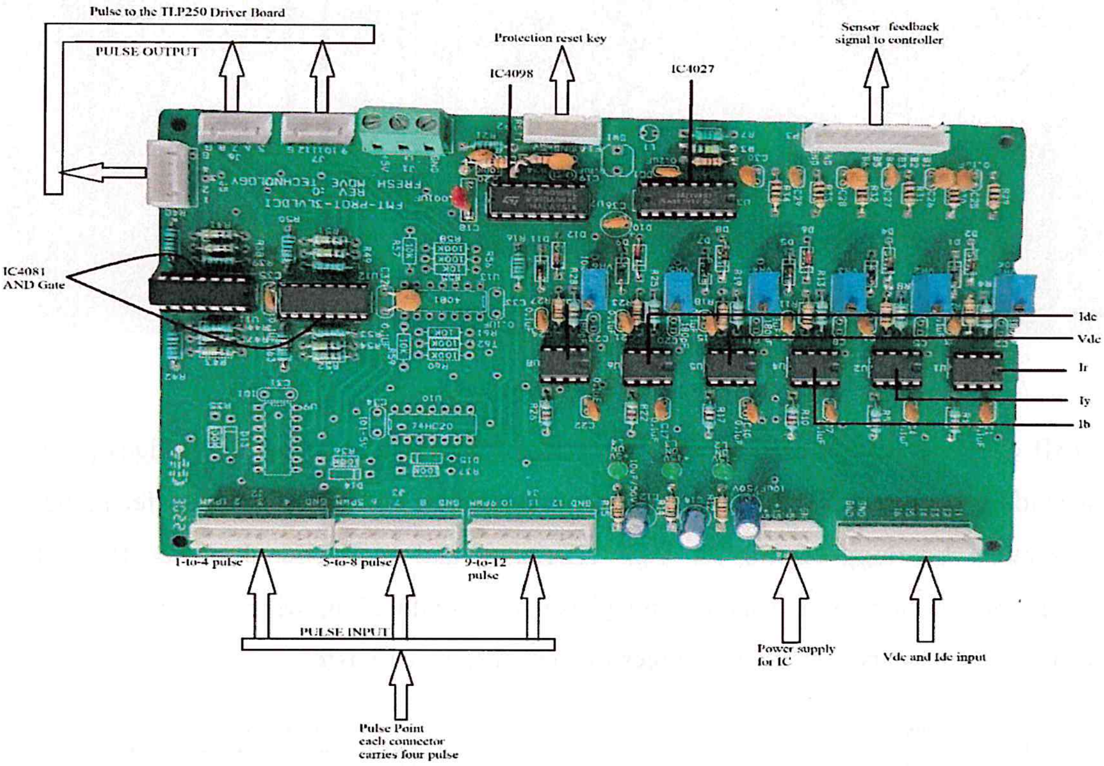

Fig. 6: Protection board

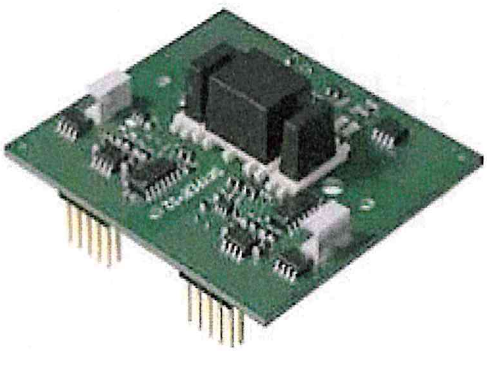

Fig. 7: Driver board

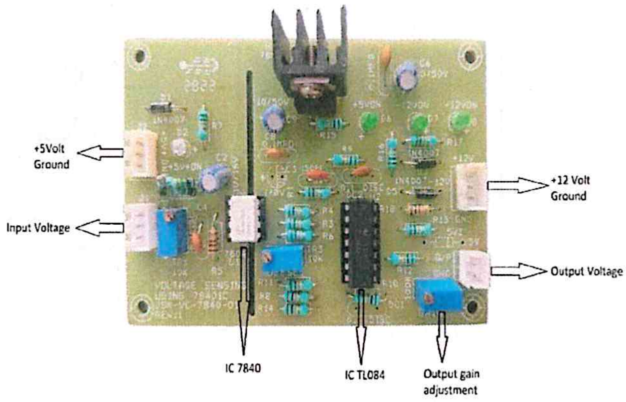

Fig. 8: Voltage sensing board

The driver board shown in Fig. 7, requires a 15-volt power supply, which is provided by the Switch Mode Power Supply. The voltage sensing board shown in Fig. 8, is responsible for monitoring both the input and output voltages of the said EV Charging system. It provides essential feedback to the controller by creating a closed-loop control system. It also ensures that the controller can adjust the system's operation in real-time, maintaining accurate voltage regulation and enhancing overall performance under varied circuit conditions. By continuously sensing the voltage levels, this board enables precise control, improving the system's stability and efficiency in various operating conditions. Fig.9, 10 illustrate glimpse of the developed Hardwired System targeting EV Charger application.

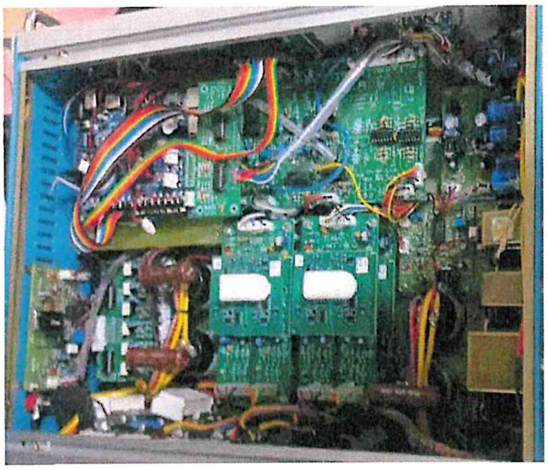

Fig. 9: Hardware set of DAB

Fig. 10: 2 kVA SST

Fig. 11: Testing setup for a high-frequency transformer-based EV charger

The image in Fig. 11 shows a testing setup for a high-frequency transformer-based EV charger connected to NIT Hamirpur procured 08 seaters electric utility passenger vehicle equipped with a 48 V battery system. The charger is currently in operation, charging the vehicle's battery pack, which is a series of 12 V Lead-acid batteries connected in series. The transformer specifications, as outlined in Table 1, play a crucial role in the functionality and performance of the DAB converter.

Table 1: Solid State Transformer Data

Power rating	2 kVA
Primary voltage	230 V
Secondary voltage	48 V
Primary current	8.7 A
Secondary current	41 A
Turns ratio	4.79 : 1
SST frequency range	40 - 85 kHz

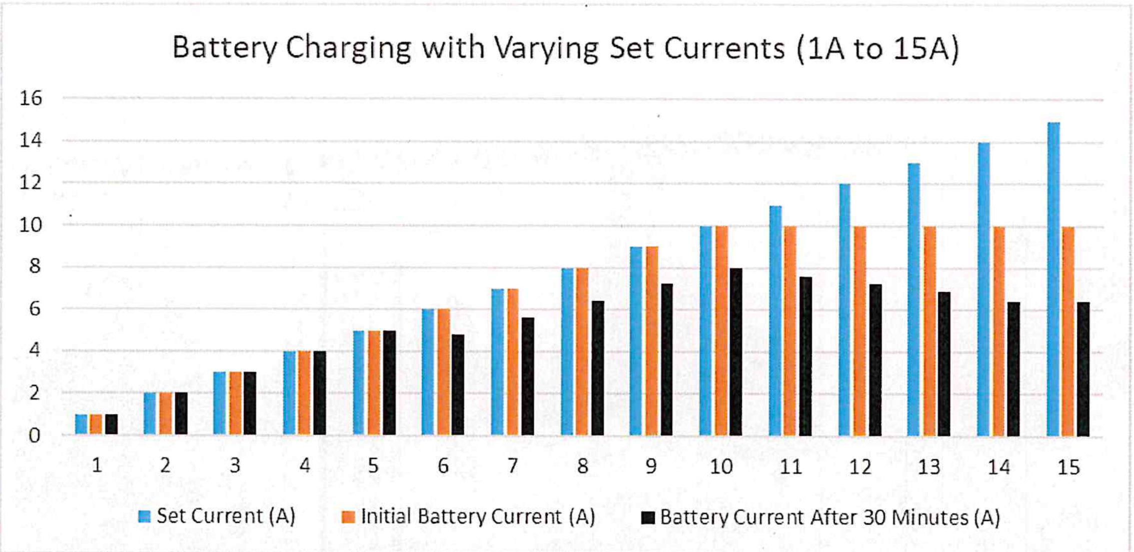

Fig. 12: Experimental results

The experimental results are shown in the Fig. 12, which illustrate the relationship between set current, initial battery current, and battery current after 30 minutes of charging during an experiment with a 48 V battery system using a high-frequency transformer-based EV charger. The experiment aims to evaluate the charging performance of an EV battery with an initial charge of 50% at different set current levels.

High Efficiency: Demonstrated impressive efficiency, achieving a maximum of 95.67% in normal operation and 93.87% in the fault state, favouring reliability and power density under varied operating conditions.

Experimental Validation: Utilized a 2 kVA converter prototype (Fig. 9 & Fig. 10) to validate findings under dynamic and steady-state conditions, confirming alignment with research objectives under varied circuit conditions for thematic applications.

Critical Design Considerations: We examined critical design considerations, including the selection of core materials, wire materials, isolation requirements, and alternative transformer structures.

Alignment with Research Objectives: This research aligns with the objective of developing industrial backup DC systems, contributing to enhanced reliability and efficiency in critical power applications.

PUBLICATIONS:

- **International Journals:**

1) M.s. Ballal, S.R. Verma, **H.M. Suryawanshi**, S.A. Wakode and Mahesh K. Mishra, "Resilient and Adaptive Power Integrator and Despatcher (RAPID)", ***IEEE Transactions on Industrial Informatics***, vol. 20, no. 05, pp.7926-7935, May-2024. [SCI]
2) R. B. Kalahasthi, M. R. Ramteke and **H. M. Suryawanshi**, "An Ultra-High Gain Quadratic Converter Based on Coupled Inductor and Switched Capacitor Techniques for DC Micro-Grid Applications", ***IEEE Journal of Emerging and Selected Topics in Power Electronics***, vol. 12, no. 02, pp. 1709-1718, April 2024. [SCI]
3) D. Govind, **H. M. Suryawanshi**, P. Nachankar, C. L. Narayana and A. Singhal, "A Modified Voltage Controller with Advanced Droop Control for Load Sharing in Standalone AC Microgrid Under Different Load Conditions," ***IEEE Transactions on Industry Applications***, vol. 59, no. 05, pp. 5818-5831, Sept.-Oct. 2023. [SCI]
4) Pratik Nachankar, **H. M. Suryawanshi,** P. Chaturvedi, Dipesh Atkar, Ch. L. Narayana and D. Govind, "Design of Interleaved Three-Phase DC Transformer with ingenious Control for Morden Data Centers," ***IEEE Transactions on Industry Applications,*** vol. 59, no. 06, pp. 6889-6899, May/Dec-2023. [SCI]

5) Mary, N. M., Sathyan, S., & **H. M. Suryawanshi,**"A Three-Level Resonant DAB Converter Featuring Minimized Circulating Losses for EV Battery Charging," ***IEEE Transactions on Industrial Electronics***, vol. 70, no. 08, pp. 7879-7890, Aug-2023. [SCI]

6) Vijay Reddy P, B.L. Narasimharaju and **H. M. Suryawanshi,** "Implementation of Dual Control MPPT-based DC-DC Converter fed Solar PV Pumping System," ***IEEE Transactions on Industrial Electronics***, vol. 70, no. 09, pp.9016-9024, Sept-2023. [SCI]

7) K. R. Kothapalli, M. R. Ramteke and **H. M. Suryawanshi,** "ZVS-ZCS High Step-up/Step-Down Isolated Bidirectional DC-DC Converter for DC Microgrid," ***IEEE Transactions on Power Electronics***, vol. 38, no. 06, pp.7733-7745, June-2023. [SCI]

8) P. P. Nachankar, **H. M. Suryawanshi**, P. Chaturvedi, D. Atkar, C. L. Narayana and D. Govind, "Design of Electric Vehicle Battery Charger with Reduced Switching Frequency Variation," ***IEEE Transactions on Industry Applications***, vol. 58, no.06, pp. 7432- 7444, Nov. 2022, [SCI]

9) P. P. Nachankar, **H. M. Suryawanshi**, P. Chaturvedi, D. Atkar and V. V. Reddy P., "Fault Resilient Soft Switching DC–DC Converter for Modular Solid State Transformer Applications," ***IEEE Transactions on Industry Applications***, vol. 58, no. 02, pp. 2242-2254, March 2022. [SCI]

10) M. S. Ballal, S. R. Verma, **H. M. Suryawanshi**, R. R. Deshmukh, S. A. Wakode and M. K. Mishra, "An Improved Voltage Regulation and Effective Power Management by Coordinated Control Scheme in Multibus DC Microgrid," ***IEEE Access***, vol. 10, pp. 72301-72311, July-2022. [SCI]

11) K. Rajesh babu, M. R. Ramteke and **H. M. Suryawanshi**, "A High Gain Low ripple SEPIC Based DC-DC Converter for Micro-Grid Applications," ***International Journal of Circuit, Theory and Applications***, vol. 51, no. 02, pp. 807-828, Feb. 2023. [SCI]

12) D. Govind, **H. M. Suryawanshi**, P. P. Nachankar, C. L. Narayana and Ankit Singhal, "An Enhanced Master-Slave Control for Accurate Load Sharing Among Parallel Standalone AC Microgrids," ***International Journal of Circuit Theory and Applications***, vol. 51, no. 2, pp. 647-667, Feb.2023. [SCI]

13) K. Rajesh babu, M. R. Ramteke and **H. M. Suryawanshi**, "A High Stup-Up Soft Switched DC-DC Converter with reduced Voltage Stress for DC Micro-Grid

Applications," ***International Journal of Circuit, Theory and Applications***, vol. 51, no. 04, pp. 1503-1969, April-2023. [SCI]

- **INTERNATIONAL/ NATIONAL PATENTS:**

National Patents				
Sr. no.	**Patent No.**	**Patent Title**	**Patentee**	**Status**
1.	545423	Machines' Monitoring, Control and Protection System (M2CPS)	**H. M. Suryawanshi**	**Granted** **22/07/2024**
2.	524684	A Process for on-line Condition Monitoring System for Static and Dynamic Electrical Machines	**H. M. Suryawanshi**	**Granted** **13/03/2024**
3.	10618	A System for The Power Quality Indices Determination with Their Causes and Effects	**H. M. Suryawanshi**	**Granted** **29-06-2022**
4.	01418	A System for Better Operation of Multi-Microgrid	**H. M. Suryawanshi**	**Granted** **29-06-2022**
5.	394522	Standardization of Three Phases Four Wire Meter as Two Phase Four Wire Meter for Traction Metering	**H. M. Suryawanshi**	**Granted** **08-04-2022**
6.	392755	Breather Condition Monitoring System for Transformers (Brecoms-T)	**H. M. Suryawanshi**	**Granted** **23-03-2022**
7.	2021103474	Digital Error Compensation of Industrial Energy Measurement System	**H. M. Suryawanshi**	**Granted** **09-03-2022**
8.	357475	Hybrid Control of Resonant Converter for DC Grid Applications	**H. M. Suryawanshi**,	**Granted** 01-Feb-2021

5. Concluding Remarks

This project successfully demonstrates the design, development, and testing of a DAB based EV charger using SST technology. Initially, a fault-tolerant, soft-switched DC-DC converter for industrial DC backup systems was developed. Leveraging this foundational work, we progressed to the design and fabrication of a 2 kW, 400/48 V prototype using planar magnetic components and SiC semiconductor devices, optimized for high-frequency and medium-frequency applications. These early experiments provided crucial insights into the material selection and performance requirements for SST components, especially in high-efficiency power conversion applications.

The core of the project focused on the exploration of different SST topologies, resulting in the identification of two-stage topologies with a low-voltage DC link as the most suitable configuration for the given application. This architecture, comprising an active front-end rectifier (AC-DC), a DC-DC stage with a high-frequency transformer, and a back-end inverter (DC-AC), has proven to be ideal due to its modularity, bidirectional power flow control, and minimized component count. Furthermore, the adoption of soft-switching techniques like zero voltage switching enhanced the overall efficiency and reliability of the system by minimizing switching losses. The DAB converter, designed for a 48 V EV battery charging system, utilized a high-frequency transformer with a power rating of 2 kVA, a turns ratio of 4.79:1, and an operating frequency range of 40-85 kHz. Experimental results validated the converter's ability to handle varying input currents efficiently. As observed during the charging tests at set currents of 1 A to 15 A, the battery's state of charge improved significantly with higher currents, demonstrating the system's ability to optimize charging times while maintaining efficiency. This research underscores the importance of SST technology in future energy systems, especially for EV charging and DC micro-grid applications. The ability to achieve bidirectional power flow, control power transfer through phase-shift modulation, and optimize component design with high frequency or medium frequency transformers makes SST a promising candidate for next-generation charging infrastructure. The versatility of the DAB converter in handling different power levels and voltages further strengthens its potential for widespread application.

In conclusion, the project successfully achieves its goals of advancing SST technology for EV charging systems. By validating the DAB converter through both simulation and hardware testing, we have shown that with the right control strategies and component design, SST-based systems can offer superior efficiency, reliability, and scalability for modern power conversion needs. This work lays the groundwork for future research in optimizing SST designs for even broader industrial and transportation applications.