High Efficiency Bidirectional Dual Active Bridge DC/DC Converter for Level 3 Electric Vehicle Charging

.

ABSTRACT

In the current scenario, slowly but surely we are getting familiar with the concept of "electric vehicles" or "charging stations".It's only been a brief period of time since the notion of "electric vehicles" or EVs has been taken up in society. Many different types of "electric vehicles" are there like hybrid, plug-in hybrid, or battery-powered "electric vehicle", one thing is clear that "electric vehicles" are intended to stay. Advancement in battery technology has allowed for lighter vehicles, longer battery "efficiency", and cost "efficiency" as well. With these developments, the public's acceptance of an alternative fueled vehicle has also grown. In this review paper design of "Dual Active Bridge (DAB) bidirectional DC/DC converter" for level 3 "electric vehicle (EV) charging" application is presented. To support battery charging and discharging applications, DAB topology is preferred due to its modular and symmetrical structure which facilitates high power throughput and bidirectional mode of operation. Simulation done using PLECS (Piecewise Linear Electrical Circuit Simulation) and MATLAB software. We have : "Single Phase Shift Control (SPS)" and "Extended Phase Shift Control (EPS)", 97% peak "efficiency" and 96% full load "efficiency", secondary "voltage": "700V-800V DC" and primary voltage: 300 V-500V DC. This design is preferred where power density, cost, weight, "galvanic isolation", high voltage conversion ratio, and reliability are critical factors.

Keywords: *Electric Vehicles; "Dual Active Bridge"; "DC/DC Converter"; "Galvanic Isolation"; "Bidirectional"; Efficiency; "Single Phase Shift Control"; "Extended Phase Shift Control".*

1. INTRODUCTION

In recent years due to rapid increase in global warming, carbon dioxide emissions has increased drastically which has lead to rise in air pollution. Over 75% of global "greenhouse gas" emissions and 90% of CO_2 emissions largest contributor are fossil fuels like gas, oil and coal. Trapping of the sun's heat happens due to the formation of blanket on the earth due to "greenhouse gases". Due to all this climate change and global warming is happening. In recorded history the world is now warming faster than at any point of time. Disruption in the usual balance of nature is happening due to warmer temperatures over time leading to changing weather patterns. This directly causes risks to human beings and all other forms of life on earth. To protect the planet, cleaning the air is one of the most direct and immediate way. Nearly 25% of "greenhouse gas" emissions are contributed by conventional transportation like IC (internal combustion) engine-based vehicles, diesel engine-based railway locomotive, heavy vehicles, airplanes and many more.

India's road transport being the second largest road network in the world contributes towards nearly 64% of the country's overall goods movement and caters to around 90% of India's total passenger traffic. This comes with challenges but also gives a huge opportunity for the decarbonization of the transport sector. By providing policy and regulatory support, government of India is actively taking measures towards creating a clean, connected, shared and cutting-edge transportation system .For achieving the target of having at least 30% new vehicle sales be electric by 2030, India has taken initiative and is among a hanful of countries that supports global EV30@30 campaign. The sale of electrical vehicles in the Indian market is projected to rise by 10X in the coming years shown in Fig.1.

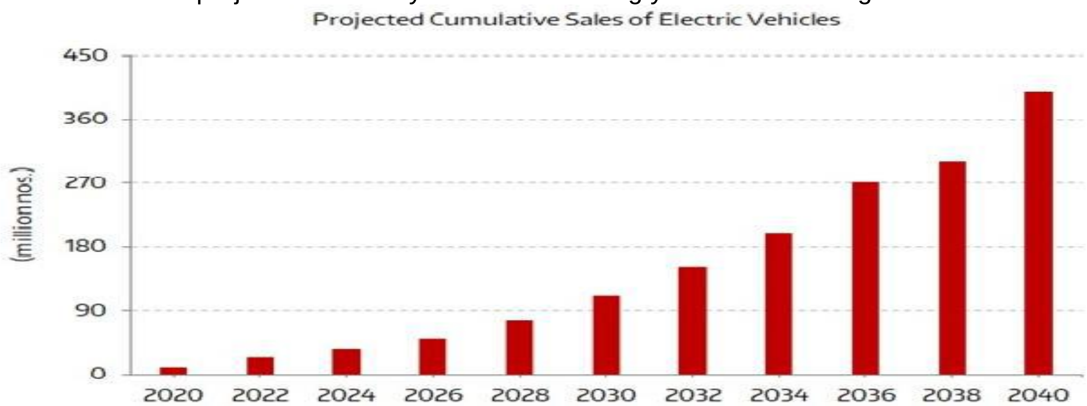

Fig. 1: Sale of Electric Vehicles for the Indian market in the coming years

2. MATERIAL AND METHODS

In the electrical vehicle charging system "power electronics converter" plays a significant role in the charging of the battery with voltage and current regulation. Mainly semiconductor based "power electronics converter" which are applied for the charging of the battery with low voltage level to high voltage level and high voltage level to low voltage level conversions. The converting function is performed by controlled semiconductor switches like SCR, BJT, power MOSFETs, IGBTs.

The "electric vehicle charging" standards which are presided by the Combined Charging System(CCS) and CHAdeMO (Charge de Move) are continuously changing and are being driven for faster battery charging rates which requires less than 30 minutes being spent at a "charging station" for full charge of an "electric vehicle" [6]. With continuous development, EVs are coming with higher ranges and batteries are get bigger. "DC charging" solutions are being developed to cater to the long-range EV batteries through developing fast charging stations up to 250 kW or more. From a three-phase Vienna rectifier at the input and battery of an "electric vehicle" at the output, the "DC/DC converter" in a charging station must be capable of interfacing with the rectified bus voltage "(700-800 V)" for delivering rated power [8]. The "DC/DC converter" finds application in a number of end equipments .Figure 2 shows application in "charging stations", solar photovoltaic systems, energy storage systems, and electric vehicle traction applications.

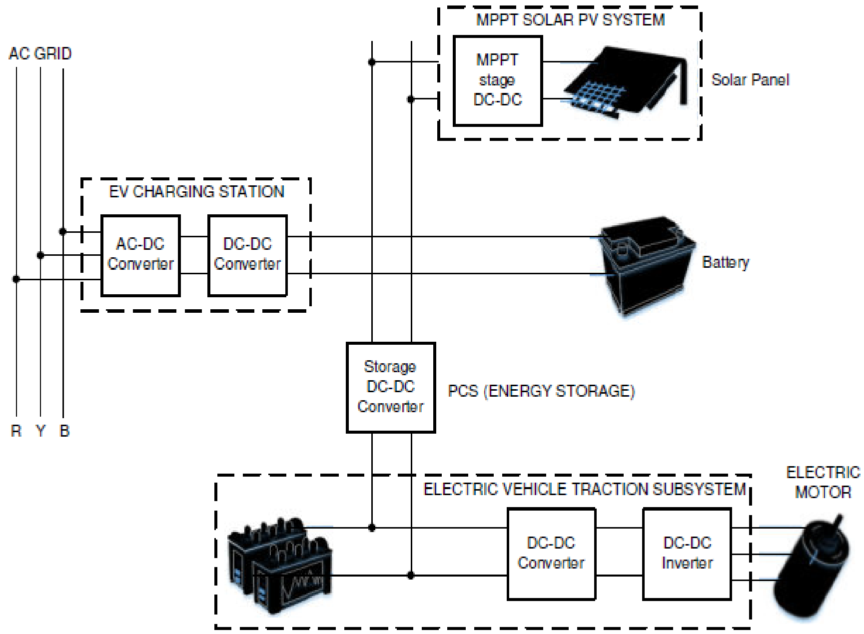

Fig.2: Role of DC-DC Converter (Texas Instruments)

2.1 EV Charging Technologies

Over the years there has been evolution in the EV chargers and currently variety of chargers are available in the market to cater different categories of EVs. Electric vehicle charging according to technological advancement can be classified into different types as shown in Figure 3. Based on the technology implemented for charging, classification can be done as follows: Conductive (plug-in), Wireless, and Battery swapping.

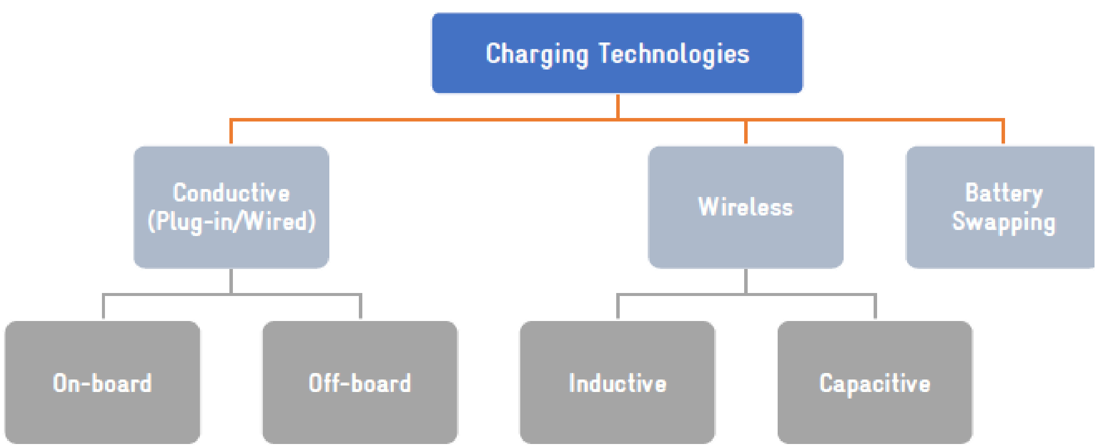

Fig.3 Classification of EV Charging Technologies

The charging infrastructure or system can be sorted in different categories on the basis of: chargers standardisation, terms of speed of charging, , ownership, charging process and directionality of power flow.

2.2 Charging Station

A charging station is basically a part of infrastructure particularly for grids which are installed along a street, parking lot or in a home garage; its primary or basic purpose is to supply the power to the vehicle for charging the battery. Mainly two types of charging systems are there, as being shown in Table 2: AC and DC charging systems. An AC charger needs vehicle's on-board charger to power the EV battery, on the other hand direct charging of the vehicle's battery takes place in case of DC charger.

Table 1: Charging Station Classification

EVSE Type	Power Supply	Charger Power	Charging Time* (approximate) for a 24-kWh Battery
AC charging station: L1 residential	120/230 V_{AC} and 12 A to 16 A (Single Phase)	Approximately 1.44 kW to approximately 1.92 kW	Approximately 17 Hours
AC charging station: L2 commercial	208–240 V_{AC} and 15 A to approximately 80 A (Single/split phase)	Approximately 3.1 kW to approximately 19.2 kW	Approximately 8 Hours
DC charging station: L3 fast chargers	300 to 600 V_{DC} and (Max 400 A) (Poly phase)	From 120 kW up to 240 kW	Approximately 30 Minutes

2.2.1 AC Charging Station

Level 1 EVSE (Electric Vehicle Supply Equipment) utilizes: 120 V_{AC}/230 V_{AC} power sources, draws current in the range of :12 A to16 A and typically takes 12 to 17 hours to fully charge a 24 kWh battery. Level1 chargers can go up to a maximum power of 2 kW and finds applications in residential areas. EVSE: level 2 finds applications in commercial spaces such as malls, offices, uses poly-phase 240 V_{AC} sources for a more efficient vehicle charger and draws: between 15 A and 80 A to completely charge a 24 kWh battery in about eight hours with power level upto 20 kW. Figure 4 shows a typical block diagram of an AC charging station.

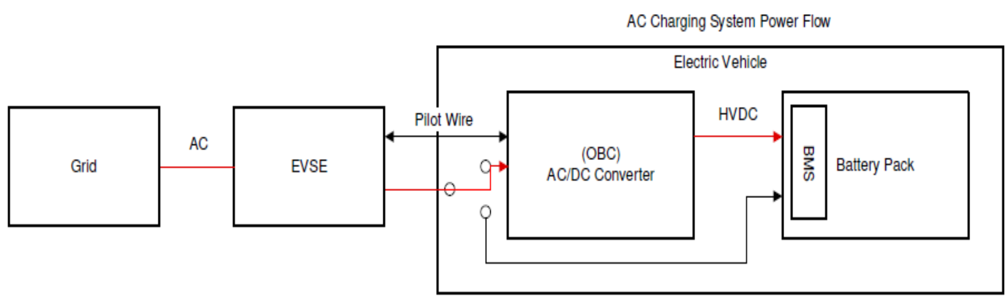

Fig.4: AC Charging Station

2.2.2 DC Charging Station

"The DC charging station is a Level 3 charger having range of 120 to 240 kW, catering for very high power level. Level3 chargers requires less than 30 minutes to charge batteries to 80% State of Charge (SOC). Modular converters which can be stacked multiple times are used to achieve such high power levels" [6]. Vehicle becomes bulky due to stacking of converters inside. Due to this reason these stacked converters are placed outside the vehicle and constitute the EV charging station. The EV charging station is interfaced with the battery of the vehicle directly, bypassing the onboard charger. Figure 5 shows a typical block diagram of a DC charging station.

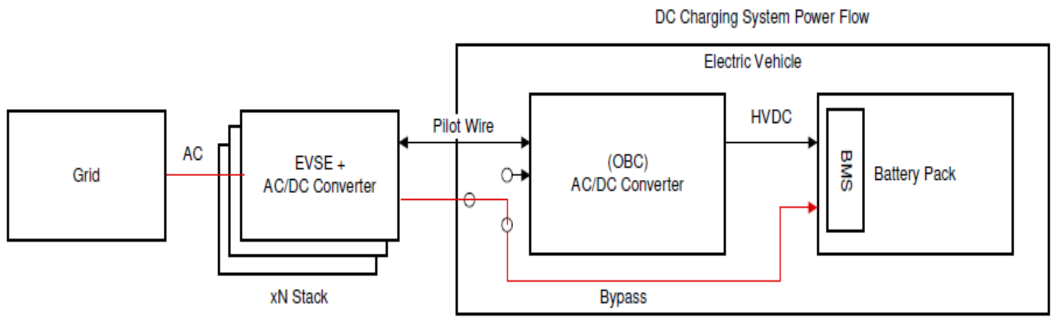

Fig. 5: DC Charging Station

2.3 Bidirectional Dual Active Bridge (DAB) DC/DC Converter

Figure 6 depicts the *Dual Active Bridge* converter. It comprises of full bridge having active switches on both primary and secondary sides which are combined together by a high-frequency transformer. ZVS is enabled and gets turn on as output capacitance of switches of one bridge of the secondary side and some switches of the primary side gets discharged due to the inherent lagging current in one of the bridges. To reduce turn off losses, lossless capacitive snubbers are used across the switches. "Modularity" enables the converter to be scaled to higher power levels and inherent "bidirectional" capability achieved by controlling the phase angle, are the main advantages of this converter.

The control of the "DAB" goes from simple one or "single phase shift modulation" to complex one (for extended, dual and triple phase shift modulation). For large variation in battery voltages with "single phase shift modulation", this topology is useful but problem comes with the drastic reduction in efficiency due to increase in the circulating currents in the transformer. The converter can theoretically achieve ZVS over the entire operating range by incorporating advanced modulation schemes like triple phase shift.

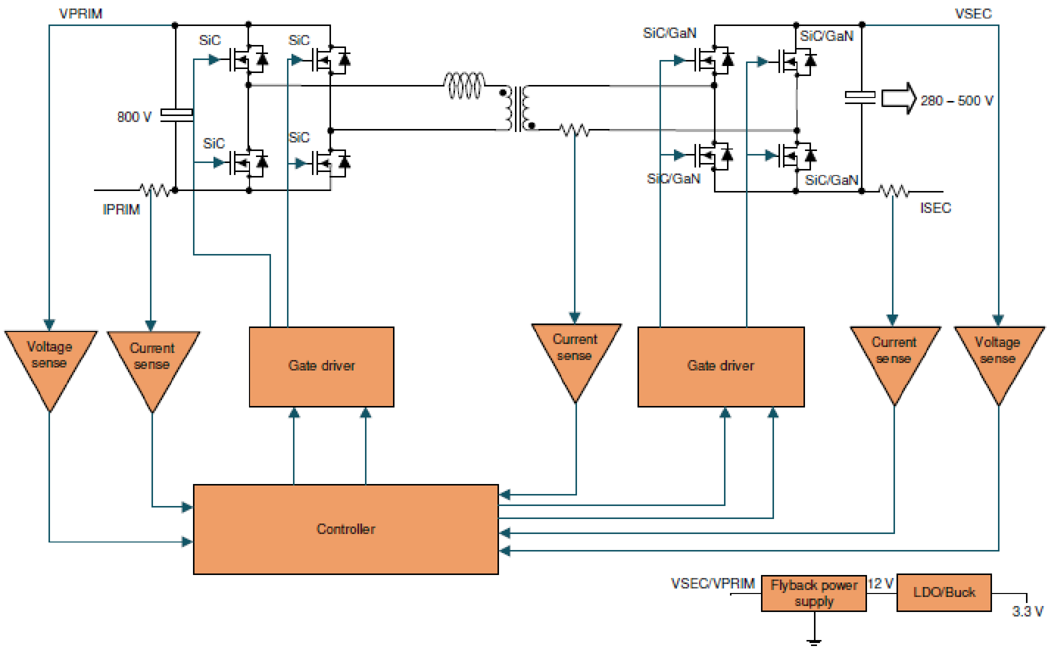

Fig.6: Dual Active Bridge DC/DC Converter (Texas Instruments)

The transformer KVA rating which is for the utilization of the output power is high for this converter topology. To handle the ripple currents, the required output capacitor value is low for this converter. This converter with features like fewer number of devices, low cost, soft-switching and "high efficiency" is suitable for applications where cost, weight, power density, isolation and reliability are important factors.

3. RESULTS AND DISCUSSION

System-level circuit of the "DC converter" have been simulated using PLECS (Piecewise Linear Electrical Circuit Simulation) and MATLAB. Simulation results are performed with "700 V- 800 V" input voltage range and 100 kHz PWM switching frequency. This design comprises of four main sections that intercommunicate:

Power stage SiC MOSFETs (metal-oxide-semiconductor field-effect transistor), system power tree, a high-frequency transformer, voltage and current sensing electronics and gate drivers.

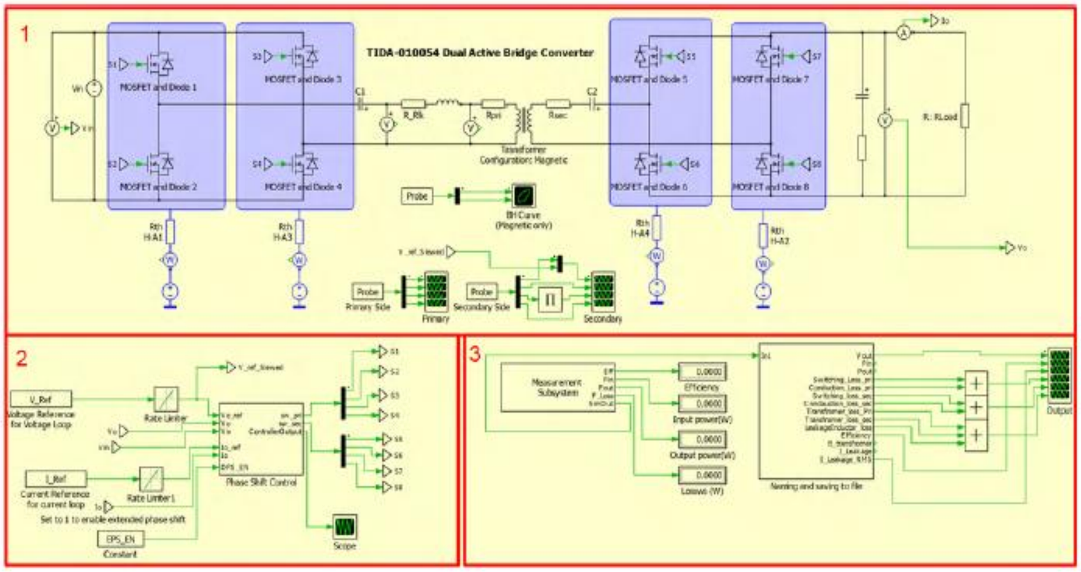

Fig.7 Simulation Environment: PLECS (Power Electronics Software)

The PLECS simulation environment consists of three major parts:

1) Power Converter:

- Silicon carbide field-effect transistor (SiC-FETs) models- power converter incorporated
- For thermal analysis we have heat sinks
- For switch node waveforms analysis we have primary scope
- Secondary scope is present to analyze current, output voltage and power
- BH Curve for the analysis of magnetic behavior of the transformer

The primary side of power stage comprises of 1200-V, 75-mΩ silicon carbide FETs for the blocking of a DC voltage of 800 V,secondary side comprises of 900-V, 30-mΩ silicon carbide FETs for the blocking of a DC voltage of 500 V. A high-frequency switching transformer (T1) is connected with the full bridges. Four heat sinks in amalgamation with two fans are used to cool the FETs. Insulation sheets are provided between the FETs and the heat sinks for necessary insulation and a good thermal interface.

2) Phase shift control:

- Comprises of controller for voltage and current loop. Switching is allowed between voltage and current loop by opening Phase Shift Control block and altering the configuration of the controller.
- Setting EPS_EN = 1 in the initialization script, we can enable the extended phase shift modulation.

3) Measurement subsystem:

- For efficiency calculation, all the losses in the system are measured and added
- During simulation running period , it displays input power, output power efficiency and losses.
- Naming signals from the measurement subsystem and saving to a file block.

Table 2 : DC Charging System Specifications

PARAMETER	SPECIFICATIONS
Input voltage range	700–800-V DC
Output voltage range	250–500-V DC
Output power rating	10-kW maximum
Output current	26-A maximum
Efficiency	Peak 98.8% (at 4 kW) full load 98.0% (at 10 kW)
PWM switching frequency	100 kHz
Power density	> 2 kW/L
Voltage ripple	< 5 %

3.1 Single and Extended Phase Shift Control

The primary side PWM pulses are phase-shifted with respect to the PWM pulses on the secondary side. The phase shift control enables power transfer between the primary and secondary and both ways. “In Dual Active Bridge topology, the maximum power transferred is very sensitive to the value of phase shift. At a small value of phase shift, a small series inductor can lead to maximum power transfer. Due to the small range over which the phase shift is going to be varied leads to accurate control requirement for the fine increment and decrement steps of phase. This is helpful in the handling of sudden load changes smoothly without producing huge overshoots or transients in the current waveforms” [6].

At the primary side we have switch node voltage (green), at the secondary side we have switch node voltage (red), inductor current (yellow).Test conditions are as follows: V_{IN} = 800 V, V_{OUT} = 450 V, I_{OUT} = 6.5 A. Figure 8 shows SPS control when the secondary side is hard-switching.

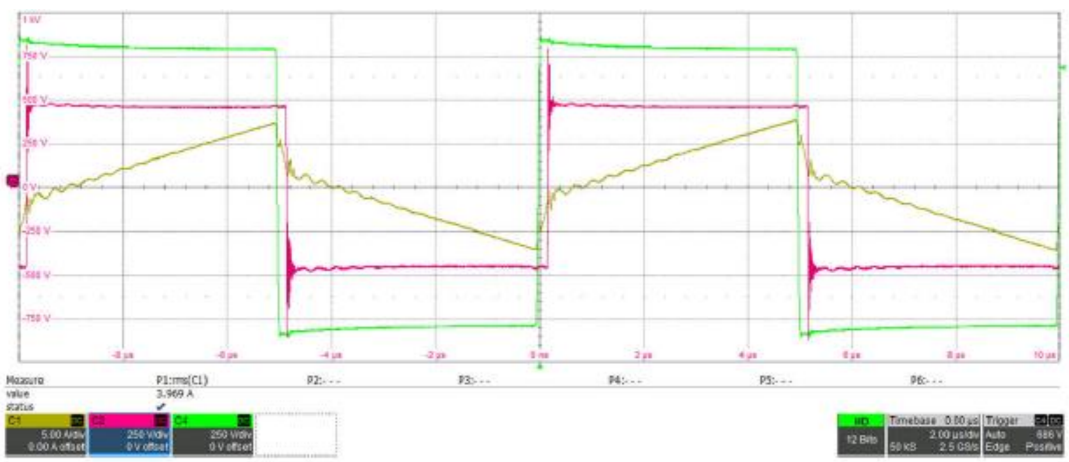

Fig. 8: Waveforms in Single Phase Shift Control (SPS)

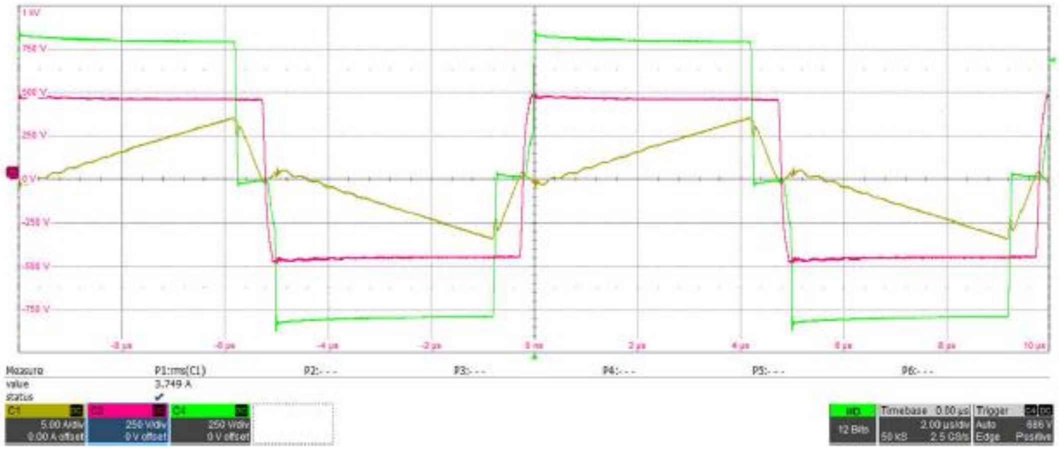

Fig. 9: Waveforms in Extended Phase Shift Control (EPS)

At the "primary side" we have switch node voltage (green), at the "secondary side" we have switch node voltage (red), inductor current (yellow).Test conditions are as follows: V_{IN} = 800 V, V_{OUT} = 450 V, I_{OUT}= 6.5 A. Here we have additional phase shift on the primary side which is introduced with EPS control as seen in Figure 9. Here primary and secondary sides both are soft-switching.

3.2 Efficiency of the DC Converter

To test the efficiency of this design we have

- Power supply of 10 kW DC: 800 V, 12.5 A
- Resistive load of 10 kW: 500 V, 20 A
- Auxiliary power supply to providing 12 V, 2 .5 A
- Power Analyzer
- Oscilloscope with isolated probes for both current and voltage
- Sufficient airflow to the heat sinks provided by 12 V fans

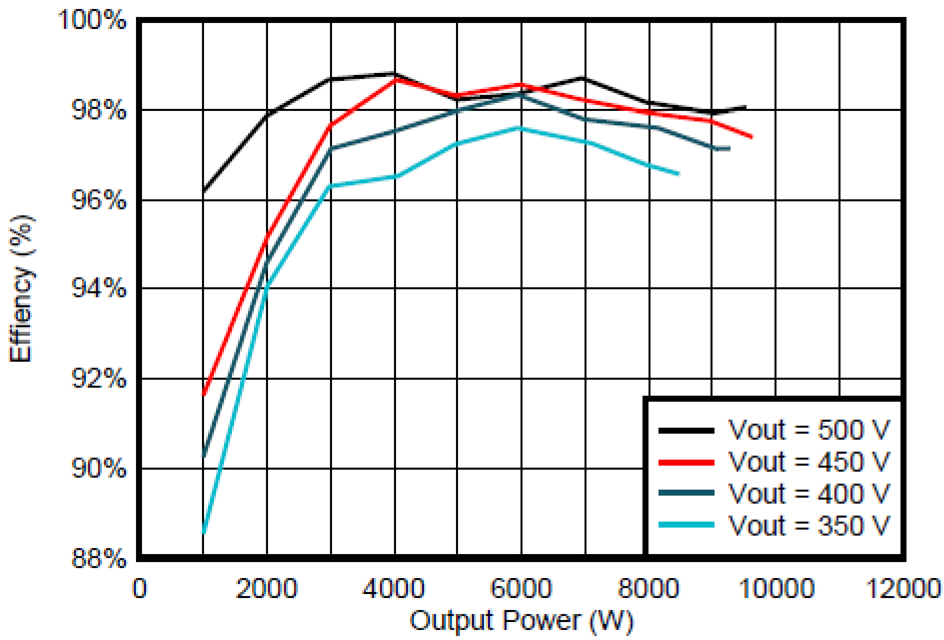

Fig. 10: Closed Loop Efficiency

The closed-loop performance was performed with output voltage control condition, figure 10 shows the results – “97% (peak)” and “96% (Full Load)”.There is an apparent drop in the efficiency of the lower output voltages. There are two main factors contributing to the drop in efficiency. Firstly due to increasing circulating currents in the system which in turn increases the RMS currents and conduction losses ultimately resulting in the lower efficiency for high loads. The second factor is ZVS for light loads which impacts light load efficiency.

4. CONCLUSION

A “bidirectional dual active bridge DC/DC converter” for level 3 EV charging has been proposed. The design works for high voltage range, “96% full load efficiency”, high power throughput leading to high power density. The design can work for both “single and extended phase shift control”. This design is reliable for long range EVs where the size of the battery gets bigger and fast charging is required, less than 30 minutes.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.
3.

REFERENCES

1.Jorge L, Concepcion H, Arjona A M, Lesedi M, Ambrish C. Performance Evaluation of an Active Neutral-Point-Clamped Multilevel Converter for Active Filtering in G2V-V2G and V2H Applications. IEEE Access.2022; 10: 41607-41621.

2. Makrygiorgou J J, Alexandridis T A. Unified Modeling, Control and Stability for a Vehicle-to-Grid and Plug-In EV System. IEEE Journal of Emerging and Selected Topics in Power Electronics2022; 10(3): 3284-3301.

3. Singh K A, Mishra K A, Gupta K K, Siwakoti P Y. High Voltage Gain Bidirectional DC-DC Converters for Supercapacitor Assisted Electric Vehicles: A Review. CPSS Transactions on Power Electronics and Applications.2022; 7(4): 386-398.

4. Shah Vaibhav, Payami Saifullah. An Integrated Driving/Charging Four-Phase Switched Reluctance Motor Drive With Reduced Current Sensors for Electric Vehicle Application. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2022; 10(6): 6880-6890.

5. Sarkar Sukrashis, Das Anandarup. An Isolated Single Input-Multiple Output DC–DC Modular Multilevel Converter for Fast Electric Vehicle Charging. IEEE Journal of Emerging and Selected Topics in Industrial Electronics. 2023; 4(1): 178-187.

6. Chaurasiya Saran, Singh Bhim. A Bidirectional Fast EV Charger for Wide Voltage Range Using Three-Level DAB Based on Current and Voltage Stress Optimization. IEEE Transactions on Transportation Electrification. 2023; 9(1): 1330-1340.

7.Jahnes M, Zhou L, Eull M, Wang W, Preindl M. Design of a 22-kW Transformerless EV Charger With V2G Capabilities and Peak 99.5% Efficiency. IEEE Transactions on Industrial Electronics .2023; 70(6): 5862-5871.

8. Arya Harshita, Das Moumita. Fast Charging Station for Electric Vehicles Based on DC Microgrid. IEEE Journal of Emerging and Selected Topics in Industrial Electronics .2023; 4(4): 1204-1212.

9. Mary M J N, Sathyan Shelas, Suryawanshi M H. A Three-Level Resonant DAB Converter Featuring Minimized Circulating Losses for EV Battery Charging IEEE Transactions on Industrial Electronics. 2023; 70(8): 7879-7890.

10. Zhang D, Huber J, Kolar W J. A Three-Phase Synergetically Controlled Buck–Boost Current DC-Link EV Charger. IEEE Transactions on Power Electronics. 2023; 38(12): 15184-15198.