Performance Of Single-Stage And Dual-Stage EV Battery Chargers For G2V And V2G Operation

Akash Ganne
Department of Electrical Engineering
National Institute of Technology
Raipur India
apganne.mtech2023.ee@nitrr.ac.in

Dr. Lalit Kumar Sahu
Department of Electrical Engineering
National Institute of Technology
Raipur India
lkumar.ele@nitrr.ac.in

2024 Third International Conference on Power, Control and Computing Technologies (ICPC2T) | 979-8-3503-4920-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICPC2T60072.2024.10474651

Abstract - In recent years the growth of electric vehicles has increased day by day and this encourages the different G2V, V2G, V2V, V2L, and V2H technologies. In this paper, discussed the bidirectional power flow from the grid to the vehicle or vice versa. V2G technology is very beneficial during peak load periods, voltage regulation, and improvement of power system stability. To implement this V2G technology, it required proper management of the electric battery charger and the charger is capable of flowing the power in either direction. This paper shows the single-stage and dual-stage charger topology to flow the power in either direction i.e. G2V or V2G. This paper also shows the battery can be charged using constant current and constant voltage charging methods. In the single stage, use only the PFC circuit to charge or discharge the battery. In the dual-stage, an active bridge rectifier for AC to DC conversion with an L filter in series with the source has been used and for the next stage, a bidirectional DAB converter with an LC filter for DC to DC conversion is used and a separate control strategy for battery charging & discharging. This paper shows the battery control strategy can charge or discharge the battery at constant current and constant voltage. The performance of this single-stage and dual-stage battery charger is verified by simulations in MATLAB/SIMULINK software and the waveform is verified in real-time using the OPAL-RT system.

KEYWORDS: G2V, V2G, electric vehicle, constant current, constant voltage, active bridge rectifier, DAB converter.

I. Introduction

The main source that provides energy to EVs is battery. Battery plays a vital role in the growth of the EV industry. To provide energy to the battery a battery charger is required. The charging system is one of the most important part of the EV system. The battery can be charged either on-board or off-board. In on board charger, the charging system and battery combinedly stay itself in an EV. All the conversion processes are done in the EV itself. In the off-board charger, the charging system is placed outside the EV. All the conversion processes in done in the charging station after that they are directly connected to the EV. The On board chargers are either single-stage or dual-stage. This can be used to charge low-voltage EVs at home [1]. The On board charger consists of PFC for AC to DC conversion stage and isolated DC to DC stage. In a single-stage on board charger, the PFC and isolated DC to DC are combined into a single power processing stage. Its advantage is that it is simple in structure and less no. of switch counts. The single-stage On board charger without an electrolytic capacitor can get power from single-phase or three-phase utility [2].

Dual-stage chargers are bulky in size, less efficient, large no. of component counts, and have very complex control circuits. To overcome these features an isolated bridgeless modified SEPIC converter is used to make a single-stage onboard charger for light electric vehicle applications. Modified SEPIC converter is used to reduce voltage stress across the switch and it is operated in DCM [3]. SEPIC converters are used to transfer the power bidirectionally i.e. G2V or V2G. This converter makes ZCS across the switches. It reduces the sensor requirement and component count and applies simple control mechanisms. It exhibits the unity power factor operation. This bidirectional battery charger is used for low-voltage applications [4].

In single-stage on board chargers, the PFC stage is for high power factor correction and increased efficiency. DCM mode makes the circuit and control algorithm very simple. This charger can be implemented very easily in DCM mode as compared to CCM mode. In CCM mode required no. of components. For DCM mode conducting the PFC stage can be made using a combination of boost and flyback converter. When compared to the two-stage charger it has less cost and higher efficiency [5]. The two-stage converter is widely used but it is costly and large. However, the converter used in a single stage has a low cost because component count is reduced, size and volume are reduced. For AC to DC conversion uses a full bridge converter in single-stage topology. In a single stage they achieve high efficiency at light load and get a high power factor at full load conditions [6]. Single-stage on board chargers are highly efficient for light load conditions but for a wide range of voltage, required two-stage topology. In the two-stage topology, there are two conversion stages first AC to DC conversion stage and the next stage is DC to DC conversion. These are connected in a cascade. Due to the presence of a second DC to DC stage, it can be applied to a wide range of voltage Levels of EV [7].

By increasing the research and advancement in power electronics components two stage on board EV chargers are getting more attention. For the PFC stage, used bridgeless converters. As is compared with bridge topology they required less no. of components, less THD. The second stage provides the isolation between two H-bridges. Providing isolation phase shift full bridge transformer is used. The phase shift full bridge transformer can be controlled using PWM switching to achieve ZVS to increase the efficiency [8]. For slow charging phase shift full bridge transformer is used. In that less amount of current flow for a long time as a result less heat will be generated. But for a fast charger, the amount of current transfer is very high and more heat will be generated. Introducing a bidirectional DAB converter for providing fast charging to EVs. In the DAB converter power can be flow bidirectionally from G2V or V2G [9]. The EV charger which is used presently it has a unidirectional characteristic it can only able to charge the EV. Implementation of V2G technology means EVs can send power to the grid whenever required[10]. This paper shows the single-stage and dual-stage bidirectional EV charger topology. Power can flow either G2V or V2G.

Section II shows the single-stage & dual-stage battery charger topology. Section III describes the different stages of charging topology. Section 4 shows modelling and control strategies to charge or discharge the battery. Section 5 represents the simulation results when it's charging i.e. the power flow from grid to vehicle (G2V) and when discharging i.e. the power flow from vehicle to grid (V2G).

II. Topology

The charger topology presented in this paper is single-stage and dual-stage. Single-stage topology uses the PFC stage for AC to DC conversion and is directly connected to the battery. Now in the dual-stage, they required two stages of conversions first AC to DC conversion i.e. PFC stage, and next DC to DC conversion which uses a DAB circuit.

A. *Single Stage Battery Charging Topology*

The given Fig. 1. shows the circuit diagram of the single-stage battery charger. Which shows only a single stage i.e. AC to DC conversion stage. In this circuit, AC power get directly from a single-phase supply and convert it into DC to charge the battery. During AC to DC conversion make sure that the power factor is unity. This stage is used for low-voltage applications.

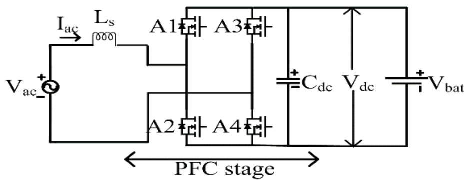


Fig. 1. Single stage battery charger

B. *Dual-Stage Battery Charging Topology*

The given Fig. 2. shows the circuit diagram of the dual-stage battery charger. It has two stages of conversion first AC to DC conversion after that DC to DC conversion. In a given circuit the first stage works exactly the same as that of a single stage. In the next stage of DC to DC conversion, provides a galvanic isolation because power is transferred at a very high frequency to charge the given battery. This stage is used for high-voltage applications and a wide range of voltage variety.

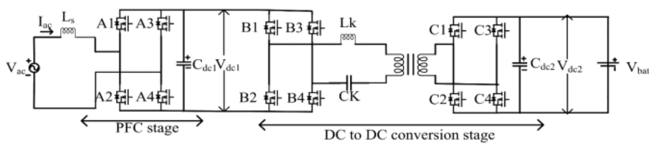


Fig. 2. Dual stage battery charger

III. Components

A. *Active Bridge Rectifier for AC To DC Conversion*

This rectifier is also known as an active front-end converter. This is the first stage of every charger that is used for the conversion of AC to DC at a high power factor. It provides a unity power factor i.e. voltage and current are in phase when power flows from grid to vehicle (G2V). This is one of the reason that it is called as power factor correction stage. Voltage and current are in opposite phases when the same power is coming from the vehicle to the grid (V2G).

The presented PFC circuit i.e. active bridge rectifier used in this circuit is very similar to the diode bridge rectifier as shown in Fig. 3. A Diode bridge rectifier draws non-sinusoidal current from the grid which creates a lot of harmonics in it which affects the load which is connected to it. Due to its non-sinusoidal nature of current and harmonics which are present in it both affect the power factor of the circuit. Due to this power factor of the circuit is getting low which directly affects the efficiency of the circuit.

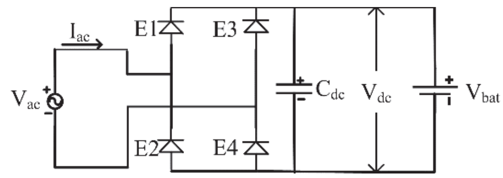


Fig. 3. Diode Bridge Rectifier

The efficiency of this circuit is low here is the one of reason due the voltage drop across the diode is more. Due to more voltage drops more heat will be generated across it which damages the equipment.

Because of the above drawback of the diode bridge rectifier circuit, given paper use an active bridge rectifier circuit for AC to DC conversion in the battery charger. In an active bridge rectifier circuit uses an active switches instead of diodes and an inductor which is connected in series with the grid as shown in Fig. 4. They perform AC to DC conversion in a controlled manner after conversion they create a common DC link voltage for further stages. Because of the inductor, they draw sinusoidal current in phase with grid voltage, reduce the no. of harmonics, and achieve unity power factor. This is the reason that this circuit is called a PFC circuit. The efficiency of this circuit is greater because the voltage drop across the switches less.

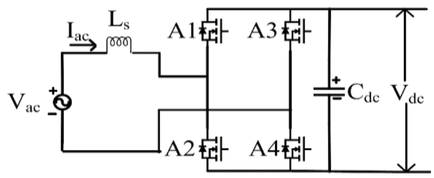


Fig. 4. Active Bridge Rectifier

B. *DAB Circuit for DC to DC Conversion*

DAB i.e. dual active bridge converters are mostly used for battery charging. DAB consists of two H bridge converters with high-frequency transformer to provide galvanic isolation between them as shown in Fig. 5. This stage provides the required DC voltage to the battery at the time of charging. This circuit uses an LC filter at the primary of the circuit to reduce the ripples in the current.

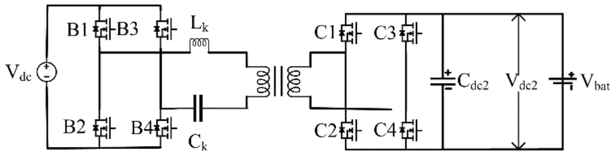


Fig. 5. DAB circuit

This is the second stage or the back end of the charger which is connected directly to the battery. This stage can be used to charge the battery of a wide range of voltage. This isolated converter is used in continuous conduction mode. This stage is used for bidirectional power flow from G2V or V2G.

C. *DC to DC Converter*

This is the DC to DC converter which is used to charge or discharge the battery at constant current and constant voltage as shown in Fig. 6. In the single stage, they get direct DC link voltage from the PFC stage and in the dual stage, they get DC link voltage from the DAB circuit at the time of charging.

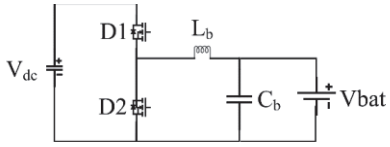


Fig. 6. DC to DC converter

It consists of two switches one is used for charging and the other is used for discharging the battery. The inductor and capacitor are used to reduce the ripples in current and output voltage.

IV. Modelling And Control Mechanisms

The control mechanisms are different for both converters. In the front-end converter, uses PI and PR control algorithms to control the switching of the converter, and for the DC to DC stage, use a single-phase shift method of switching. For constant current & constant voltage charging, uses an PI controllers.

A. PFC Stage

In this stage AC to DC conversion is done by keeping the 400v at output as a DC link voltage by controlling the grid current and the PWM switching of the converter. The grid is connected to 1 phase 230v rms. It consists of 4 active switches (A1 to A4), source inductance(L_s), and one output filter(C_O).

When the AC supply is connected across the switches it creates a sinusoidal waveform of grid voltage and current which are in phase. By using two complementary switches (A1 A2)&(A3 A4) and making a 50% duty cycle it creates a constant DC voltage at the end.

1) During Positive Half Cycle

During the positive half cycle of the AC supply switch A1 and A4 are conducted and A3 and A4 are off. This is forwarding mode by conducting the A1 and A4 switch. The current completes its path as shown in the Fig. 7.

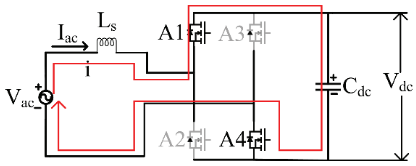


Fig. 7. AC to DC converter during positive half cycle

When switches A1 and A4 are conducting the voltage across the inductor,

$$V_L = L\frac{di_g}{dt} = V_g - V_{dc} < 0 \tag{1}$$

2) During a Negative Half Cycle

During the negative half supply switches A1 and A4 are turned off and switches A2 and A3 are turned on in this stage. This is the reverse conducting mode. The current completes its path in the reverse direction as shown in Fig. 8.

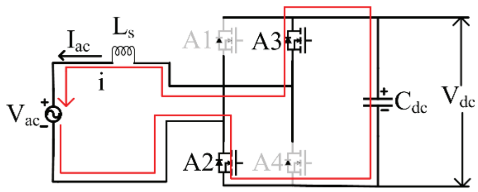


Fig. 8. AC to DC converter during negative half cycle

When switches A2 and A3 are conducting the voltage across the inductor,

$$V_L = L\frac{di_g}{dt} = V_g + V_{dc} > 0 \tag{2}$$

In each case, the output voltage V_{dc} is always greater than the grid voltage V_g.

Power factor is determined by using 1) offset and 2) phase angle between voltage and current.

Power factor = $\cos\theta$

The conventional method to find the power factor

$$\text{power factor} = \frac{\cos\theta}{\sqrt{1 + (THD)^2}} \tag{3}$$

where THD i.e. Total harmonic distortion is defined as,

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n,rms}^2}}{I_{1rms}} \tag{4}$$

From equation (3) it is clear that the power factor is inversely proportional to the THD. THD depends on harmonics which are present in the current. By controlling the switching of the circuit reduces the harmonics in the current. By reducing the harmonics in current improve the power factor of the circuit.

3) Control mechanisms

Used PI & PR controller for controlling the switching of the circuit as shown in Fig. 9. This controller uses three major quantities 1) grid voltage 2) grid current 3) output DC voltage

The PLL is employed to find the voltage phase which maintains a high power factor. There are two control loops: one is the outer loop which is used to control the output DC link voltage and the inner loop is used to control the current.

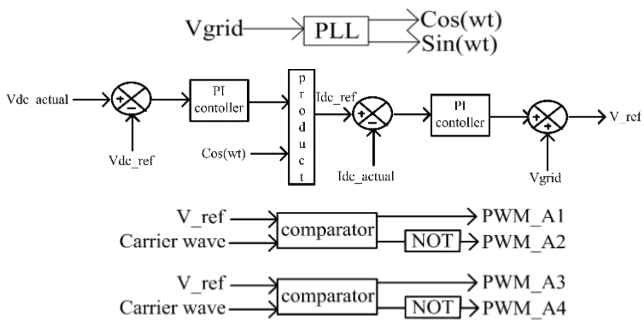


Fig. 9. control loop for PFC stage

For supplying real power from the grid to the vehicle PLL creates an active ref. current signal which is in phase with voltage for G2V operation. For getting power back to the grid PLL also creates a reactive ref. current signal which is out of phase with voltage for V2G operation.

There are two switching methods are used for PWM signals. They are unipolar switching and bipolar switching. In this control algorithm, uses an the unipolar switching method to switch the active switches.

By using this control algorithm maintain the power factor at unity and regulate the output DC link voltage in a range of 350V to 800V.

B. DAB Converter with LC Filter

This converter is used to charge the battery. It is a simple DC to DC converter using two H bridge and one transformer in which the LC filter is connected at the prim. It consist of 8 (B1-B4 & C1-C4) switches and the input comes from the PFC circuit as shown in Fig. 10.

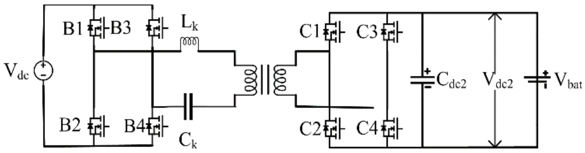


Fig. 10. DAB converter

During the positive half cycle B1 and B4 switches of the primary are conducted and after some delay, the switches C1 and C4 are conducted. Similarly, in the negative half cycle switches B2 and B3 of the prim are conducted and after some delay switches C2 and C4 are conducted.

$$Delay \; = \; phase\ shift \; = \alpha$$

The switching of the dab converter is better understood by using waveform in 8 modes of operations.

Mode (T0 -T1) = prim. switches B1/B4 & C2/C3 are conduct. In this mode the inductor current change its state from -ve to +ve.

Mode (T1 – T2) = In this mode B1/B4 and C1/C4 are conduct simultaneously. In this mode, the inductor current is still positive but in an increasing manner.

Mode (T2 – T3) = In this mode the switch B2/B3 is conducted in the negative half of prim. H bridge and switch C1/C4 are conduct in the positive half of the sec. of H bridge. In this mode the inductor current increases in the +ve direction.

Mode (T3 – T4) = In this mode the switches B2/B3 of prim. H bridge and switches C2/C3 of sec. H bridges are conducted simultaneously in the negative half cycle. In this mode the inductor current increases.

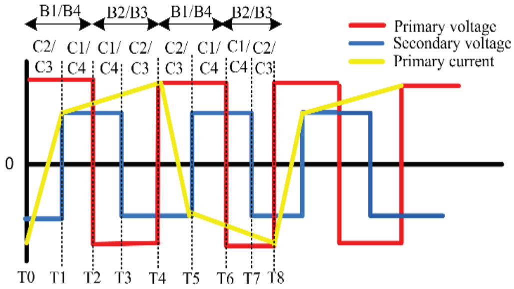
Mode (T4- T5) = In this mode the switches B1/B4 of prim. H bridge in the positive half cycle and C2/C3 of sec. H bridge in the negative half cycle. In this mode, the inductor current decreases and changes its state from +ve to -ve direction.

Mode (T5 – T6) = In this mode the switch B1/B4 is conducted in the positive half of prim. H bridge and switch C1/C4 are conducted in the positive of the sec. of H bridge. In this mode, the inductor current decreases in -ve direction.

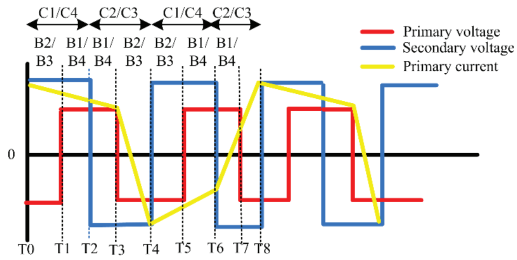
Mode (T6 – T7) = In this mode the switches B2/B3 of prim. H bridge are conducted in the negative half cycle and switches C1/C4 of sec. H bridges are conducted in the positive half cycle. In this mode, the inductor current still decreases in a negative manner.

Mode (T7 – T8) = In this mode the switches B2/B3 of prim. H bridge and C2/C3 of sec. H bridges are conducted in simultaneously the negative half cycle. In this mode, the inductor still decreases negative manner.

These 8 mode of operation for valid for G2V operation. For V2G operation the inductor current gets reversed. When the secondary voltage is more than the primary voltage is shown in the above Fig. 11 (a) & (b). This dab converter achieve high efficiency because switching losses are less.



(a)



(b)

Fig. 11. (a) switching of switches & current direction when G2V operation in occurs ($V_i > V_o$). (b) switching of switches & current direction when V2G operation in occurs ($V_i < V_o$)

Switching losses can be reduced by increasing the switching frequency of the system. By increasing the switching frequency means getting ZVS i.e. zero voltage switching is here. zero voltage switching is a type of soft switching. It switches the circuit when the voltage is zero. Phase shift is dependent upon the output voltage. Output capacitor as a DC link capacitor is made as large as possible to maintain constant output voltage.

To find the filter value requires the resonant frequency less than the switching frequency and select the range of DAB current.

The output power transfer by DAB

$$P_0 \; = \; \frac{V_i \, * \, V_0}{n\pi f L_k} \emptyset(\pi - \emptyset) \tag{6}$$

The direction of the power flows can be seen by using the above current waveform shown in Fig. 12 (a), (b) & (c).

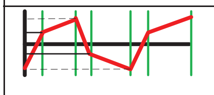
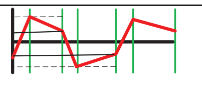
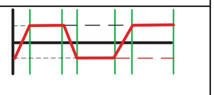
For G2V $V_i > V_o$	For V2G $V_i < V_o$	Form same voltage on both side $V_i = V_o$
		
(a)	(b)	(c)

Fig. 12. current directions (a) when $V_i > V_o$ (b) when $V_i < V_o$ (c) when $V_i = V_o$

1)Control mechanisms

For switching the 1st H bridge makes the PWM signals from the pulse generator by making a 50% duty ratio.

For switching the 2nd H bridge makes the same PWM signal from the pulse generator but it passes through time variable delay to ensure that there is a phase shift between prim. and sec.

For controlling output voltage using PI controller as shown in Fig. 13.

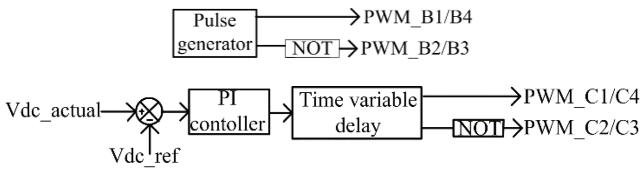


Fig. 13. control mechanisms for DAB converter

C. DC to DC Controller for Battery Charging.

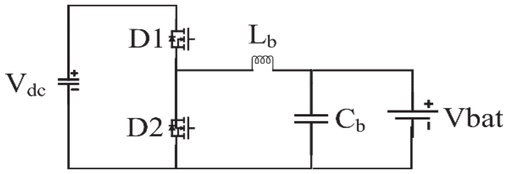


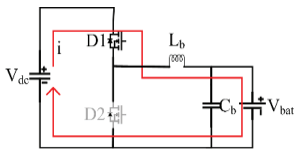
Fig. 14. charger configuration

This is the DC to DC converter which is required to charge or discharge the battery at constant current and constant voltage. It consists of two switches one is used for charging and the other is used for discharging the battery. The inductor and capacitor are used to reduce the ripples in current and output voltage shown in Fig. 14.

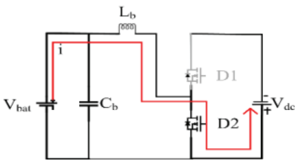
1) During Charging & Discharging

During charging the power flows from grid to vehicle (G2V). In this mode, the switch D1 is conducting and the flow of current is as shown in Fig. 15 (a). In this condition they get input from DAB and converted into output to charge the battery.

During discharging the power will be from the vehicle to the grid (V2G). In this mode switch D2 is conducting and the flow of current is as shown in Fig. 15 (b). In this condition they supply energy from the battery and give it to the DAB converter in the dual-stage and in the single stage they give it to the direct grid.



(a)



(b)

Fig. 15. Charger configuration during (a) charging (b) discharging

For controlling the switching of this converter using PI controller as shown in Fig. 16.

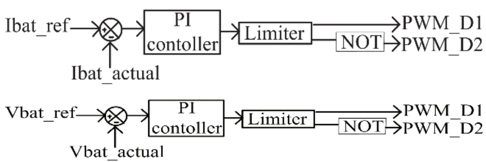


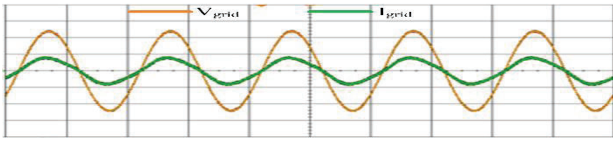
Fig. 16. controller for constant current & constant voltage charging/ discharging

V. RESULTS

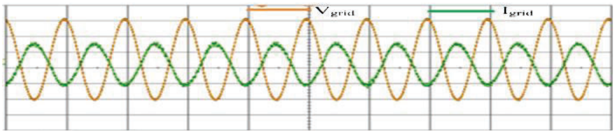
Presented paper shows the implement the single-stage and dual-stage bidirectional battery charger using MATLAB/SIMULINK and the results are shown above.

A. Single-stage battery charger

The charging circuit uses a single-stage charger its performance waveform is shown in above. It charges or discharges the std. battery 300V, 150Ah at a constant current and constant voltage. At the time of charging grid voltage & grid current are in phase. When the battery is discharging the grid voltage & current are out of phase as shown in Fig. 17(a) & (b).



(a)

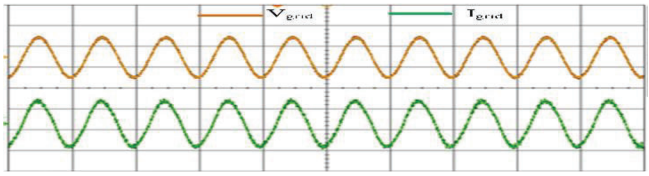


(b)

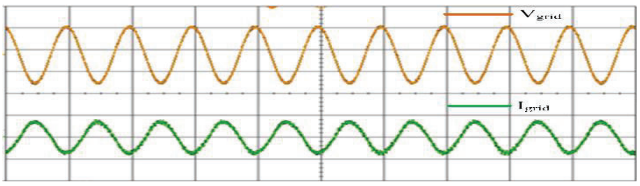
Fig. 17. (a) grid voltage & grid current are in phase at the time of charging i.e. G2V, (b) grid voltage and grid current are out of phase at the time of discharging i.e. V2G

B. Dual-Stage Battery Charger

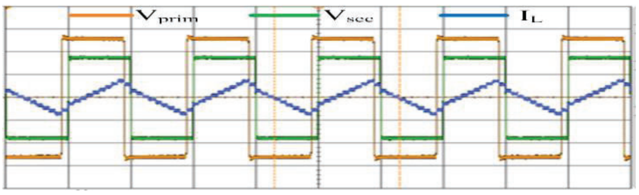
The simulation results of the described bidirectional dual-stage EV charger are as follows. When G2V operation is performed grid voltage & current are in phase. DAB waveform at the time of charging prim. voltage is greater than sec. voltage. When V2G operations are performed, that time grid voltage & grid current are out of phase also the DAB waveform at the time discharging sec. voltage is greater than prim. voltage as shown in Fig. 18 (a), (b), (c) & (d).



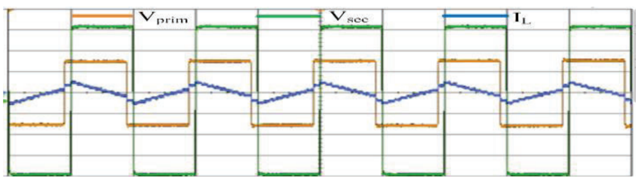
(a)



(b)



(c)

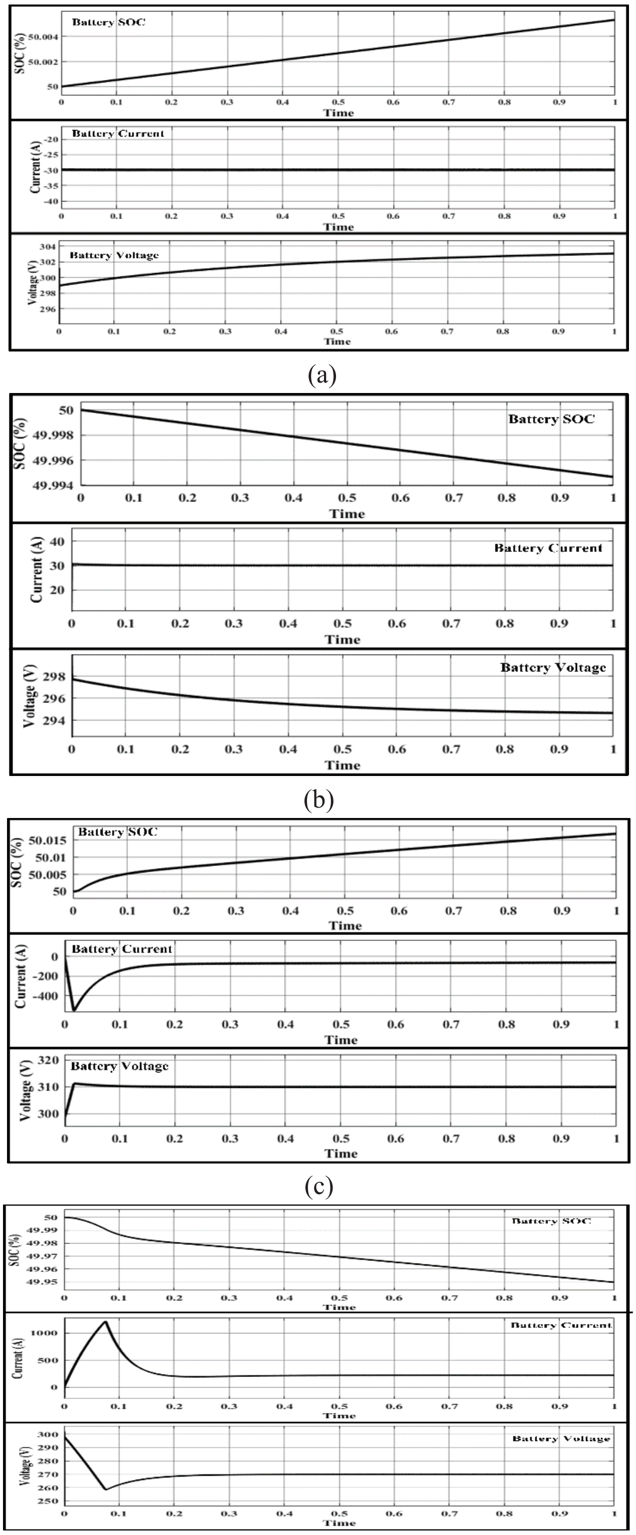


(d)

Fig. 18. (a) grid voltage & grid current are in phase at the time of charging i.e. G2V operation (b) grid voltage and grid current are out of phase at the time of discharging i.e. V2G operation (c) DAB waveform at the time of charging i.e. G2V operation (d) DAB waveform at the time of discharging i.e. V2G operation

C. *Battery charging/discharging at constant voltage and constant current*

By using the described battery charger controller , charge or discharge the battery at constant voltage & constant current. The above simulation results shows the battery current, battery voltage, & soc of the circuit at the time of charging/discharging as shown in Fig. 19.



(a) (b) (c) (d)

Fig. 19. Simulation results of (a) battery charging at constant current (b) battery discharging at constant current (c) battery charging at constant voltage (d) battery discharging at constant voltage

VI. Conclusion

This paper described the single-stage & dual-stage bidirectional battery charger which is used to provide power from a grid to a vehicle (G2V) operation and vice-versa. Presented paper shows G2V operation is for charging of the battery & shows the battery can be charged or discharged at constant current & constant voltage and vice-versa. This paper uses zero current switching to reduce the switching losses of the converter. This paper shows the power can flow in either direction G2V or V2G. The results of the various stages are tested and validated using MATLAB/SIMULINK software & get the results in real-time using the OPAL-RT system.

References

[1] A. K. Singh and M. K. Pathak, “A comprehensive review of integrated charger for on-board battery charging applications of electric vehicles,” in 2018 IEEE 8th Power India International Conference (PIICON), 2018.

[2] H. Kim, J. Park, S. Kim, R. M. Hakim, H. P. Kieu, and S. Choi, “Single-stage EV on-board charger with single- and three-phase grid compatibility,” in 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021.

[3] A. Singh, J. Gupta, and B. Singh, “Design of Single-Stage Light Electric Vehicles Battery Charger based on Isolated Bridgeless Modified SEPIC Converter with Reduced Switch Stress.” 2022 IEEE 1st Industrial Electronics Society Annual On-Line Conference (ONCON), 2023.

[4] J. Gupta and B. Singh, “A Fully Bridgeless Bidirectional Single Stage Isolated Battery Charger for Low Voltage Electric Vehicles.” 2022 IEEE 10th Power India International Conference (PIICON): IEEE, 2023.

[5] A. Singh, J. Gupta, and B. Singh, “A Single-Stage Isolated High Power Factor AC-DC Converter based Battery Charger for Light Electric Vehicle.” 2022 IEEE 10th Power India International Conference (PIICON): IEEE, 2023.

[6] F. Kurokawa and S. Hattori, “Single stage AD-DC full-bridge converter for battery charger,” in 2015 IEEE International Telecommunications Energy Conference (INTELEC), 2015.

[7] B. T. Vankayalapati, R. Singh, and V. K. Bussa, “Two stage integrated on-board charger for EVs,” in 2018 IEEE International Conference on Industrial Technology (ICIT), 2018.

[8] S. Sumith and D. Krishnan, “Two stage electric vehicle battery charger with on-board topology,” in 2021 International Conference on Communication, Control and Information Sciences (ICCISc), 2021.

[9] K. Viji, K. Chitra, and M. S. Sujatha, “Fast Charging Technique for Grid Connected Electric Vehicle using DAB Converter.” 2022 3rd International Conference on Communication, Computing and Industry 4.0 (C2I4): IEEE, 2023.

[10] Y. Zhao, *“Application of Bidirectional Dual-Active Bridge Converter on EVs Fast Charging System.”* 2023 Panda Forum on Power and Energy (PandaFPE) : IEEE, 2023.

[11] W. Zhang, J. Song, C. Xu, L. Lin, H. Ren, and Y. Gao, “Implementation of constant current or constant voltage output based on switching circuit for battery charging applications,” in *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*, 2021.