A HIGH-POWER FACTOR BIDIRECTIONAL BATTERY CHARGERUSING SINGLE-PHASE MATRIX CONVERTER

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Abstract

This paper presents a novel unity power factor bidirectional battery charger using single-phase matrix converter (SPMC). The advantages of the proposed converter are its capability to perform bidirectional operation for charging and discharging purposes hence low harmonic distortion in supplycurrent and nearly unity power factor over a wide operating output power range. Its circuit has employed only single circuit topology that is SPMC and by using the proposed switching algorithm it can be controlled for both charging and discharging operations resulting reduces the cost and enhances the system's efficiency. Thus, the proposed converter incorporating with an active current controller improves the line power quality and delivers admissible output power to the battery. Computer simulation results using MATLAB/Simulink based on a 24-V battery charger are proposed to validate the proposed approach and to demonstrate its performance.

Keywords: *Bidirectional Battery Charger, Single-Phase Matrix Converter, Unity Power Factor*

Introduction

Recently, batteries are widely used in the application of residential, industrial, commercial energy storage systems and in electric vehicle (EV) technologies because of their reduced fuel usage and greenhouse emissions resulted in increasing the demand and the use of batteries charger. As a result battery chargers play a critical role in the development of these application where the converter is needed to interface between dc or ac voltage buses where energy generation and consumption devices are installed. In addition, a battery charger must be efficient and reliable, with high power density,low cost, and low volume and weight. The conventional battery charger system, which extracts power from an AC line source, requires a diode or thyristor rectifier in order to convert into DC form and to control the charging power flow. As a results, the presence of deleterious harmonics may potentially pollute the electrical supply system effecting induce voltage distortion and increase losses, eventually leading to premature failure of electrical equipment. Hence, there is very important to develop naturally clean new power converter topology that inject very low harmonic content into the power grid and operate at nearly unity input power factor.

In addition, a unidirectional charging system classified as a logical first step because it limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation has been commonly considered and studied in numerous technical papers [1]. The unidirectional charging system encounters drawbacks such as its limitation of controllability for power conversion operation to charging or discharging. To alleviate these drawbacks, a topology that is suitable for dc loads and is powered from ac sources able to invert the voltage at the same time should be developed.

The matrix converter is an AC-AC power converter topology based mainly on semiconductor switches with minimal requirements for passive components. It consists of a matrix of bi-directional switches arranged such that any input phase can be connected to any output phase. The matrix converter offers many potential benefits to the power converter industry. It will not be the best solution for all uses but it offers significant advantages for many different applications. Indeed, matrix converter is a key technology when high efficiency and reliability are required. The main building block of the matrix converter is the bidirectional semiconductor switch. Single device that can both conduct current in each direction and block voltage in both directions. If a single-phase matrix converter using a typical bi-directional switch connected in common emitter anti parallel with diode pair arrangement, 8 IGBT's and 8 diodes are needed together with associated gate driver circuitry.

In this work, a bidirectional charging system supports charge from the grid and battery energy injection back to the grid is proposed. By using single-phase matrix converter topology, a proper switching algorithm is developed to control the switches in order to perform rectifier operation for charging purpose and an inverter operation for discharge energy from the battery to the grid. By incorporating a series inductance, we also studied the behaviour of active current control to achieve unity power factor through rectifier boost technique. Successful investigations of this proposed topology lead to high performance bidirectional battery charger using single- phase matrix converter incorporating with power factor corrected.

Conventional Bidirectional Battery Charger

The bidirectional battery charger system that provides a high level of power quality at input mains with reduced THD, high power factor, ripple-free and regulated dc output voltage insensitive to load and supply disturbances have been reported with various topologies and schemes [2]. These chargers are divided into half-bridge as shown in Fig. 1 and full-bridge topologies as shown in Fig. 2, where the half-bridge has an advantage such as fewer components and lower cost, but has disadvantage such as exhibits high component stresses. However, the high components stresses can be solve using the full-bridge systems, but resulted to have more components and higher cost [3].

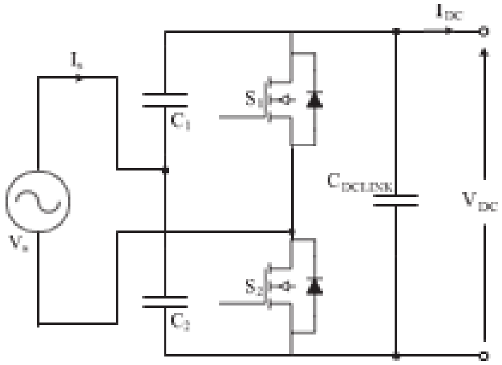

Figure 1 Single-Phase Half-Bridge Bidirectional Chargers

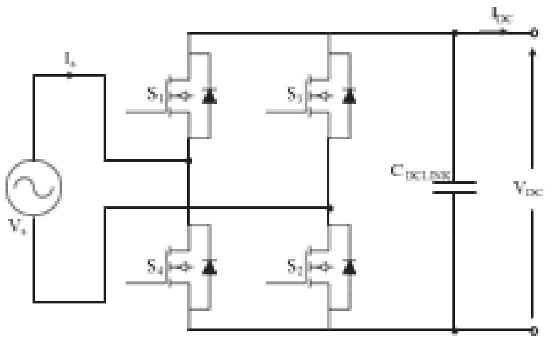

Figure 2 Single-Phase Full-Bridge Bidirectional Chargers

Single-Phase Matrix Converter Topology

The simple topology of the matrix converter with the possibility of greater power density and easy control of the input power factor has recently rise it been the subject of lot of research works [4]. As a result, its make this topology becomes a suitable alternative to the conventional voltage source inverter (VSI) circuit topology that could be used to feed all type of dc or ac loads using various control techniques. However, several disadvantages of the matrix converter such as a limited voltage transfer ratio, the complexity of the converter protection system; more sensitive to grid voltage distortions and the high number of power switches resulted more costs are added. Several research works proposed some solutions for cost and size reduction such as development of SPMC with reduced switches count have been presented in numerous technical papers [5-6].

The single-phase matrix converter consists of a matrix of four bidirectional switching elements as shown in Fig. 3 such that there is a switch for each possible connection between the input and output lines

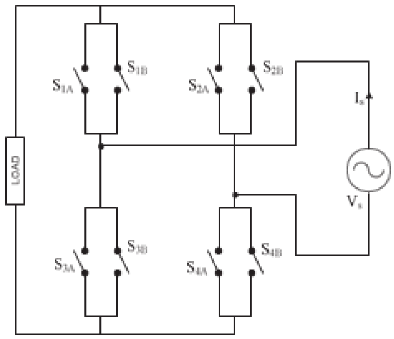

Figure 3 Single-Phase Matrix Converter Topology

Proposed Unity Power Factor Bidirectional Battery Charger using SPMC

The proposed unity power factor bidirectional battery charger using SPMC illustrated in Fig. 4 has the fully controllable symmetric structure of the primary rectifying stage and the secondary inverting stage. By using the proposed switching algorithm as tabulated in Table 1, the power switches are controlled to converts power from ac or dc to dcor ac. In addition, Fig. 4 also shows power flow directions in the converter, which are defined as follows: charging mode (forward power flow direction convert from ac to dc) and discharging mode (backward power flow direction from dc to ac).

Table 1 Switching Algorithm for the Proposed Unity Power Factor Bidirectional Battery Charger using SPMC

Switches	Charging mode		Discharging mode	
	Positive cycle	Negative cycle	Positive cycle	Negative cycle
S1a	**Off**	**On**	**On**	Off
S1b	**PWM**	**Off**	**Off**	Off
S2a	**Off**	**Off**	**Off**	On
S2b	**Off**	**On**	**Off**	Off
S3a	**On**	**Off**	**Off**	On
S3b	**Off**	**PWM**	**Off**	Off
S4a	Off	Off	On	Off
S4b	On	Off	Off	Off

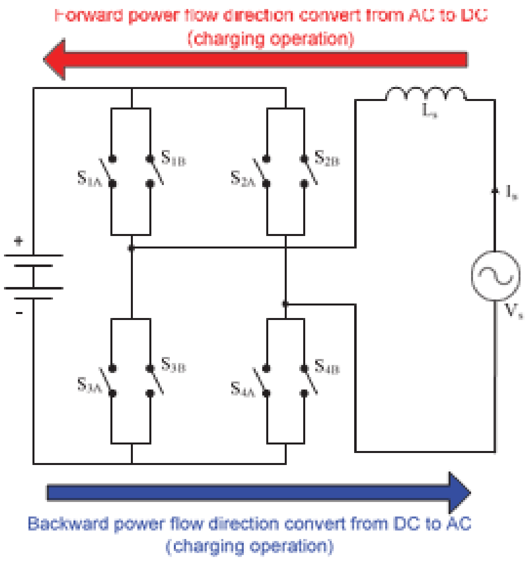

Figure 4 Proposed Unity Power Factor Bidirectional Battery Charger using SPMC

Charging Mode

Fig. 6 shows charging operational modes of the proposed unity power factor bidirectional battery charger using SPMC. This converter has six operational modes during a single switching cycle. Mode 1, 2, and 3 discuss the operation during positive cycle operation whilst mode 4, 5, and 6 with different switch and rectifier pairs discuss the operation during negative cycle operation. Mode 1 and 4 are storing energy to boost changed. The current passing through the S1a and 2b can makethe inductor store enough energy for power factor correction using boost technique.

Mode 5 [t_4 – t_5]: S2b and S3b turn ON whilst S1a turn OFF, and the converter starts to transfer power from the ac side tothe dc side. During this mode, the battery starts to charge.

Mode 6 [t_5 – t_6]: This mode is also a dead-time duration inductor durations. Mode 2 and 5 are power transfer modes from the ac side to the dc side, and Mode 3 and 6 are dead-time duration. While power is transferred from the ac side to the dc side (charging mode), the SPMC switches are controlled to operate in the rectifier mode; however, the SPMC switches are controlled to operate as inverter in the inverting mode (discharging mode). Fig. 5 shows theoretical waveforms of the proposed converter for all modes during a single switching cycle. There are the waveforms of the reference current and generated active pulse width modulation signal (APWM) during charging mode. Detail descriptions and explanations of the operational modes are as follows:

Mode 1 [t_0 – t_1]: This mode is a boost inductor storing energy duration; there is no power transferred to the dc side in this stage. The current charges the inductor through switches S3a and S4b. After charging process, the current will pass through the switch S1b.

Mode 2 [t_1 – t_2]: At this stage, switch S3a is turn OFF whilst S1b and S4b turn ON and power will be transferred to the dc side in rectifying stage. Therefore, the battery is starts to charge in this stage.

Mode 3 [t_2 – t_3]: This mode is a dead-time duration; there is no power transferred to the secondary rectifying stage. The switch S1b is turn OFF, and the switch pair of S3a and S4b are turn ON.

Mode 4 [t_3 – t_4]: The operation during this mode is similar to Mode 1; however, the charging of the switch pair is with the switch pair of S1a and S2b turn ON. Without power transfer through S3b, the battery is becomes disconnected fromthe ac side.

Discharging Mode

As shown in Fig. 7 the discharging operational modes of the proposed unity power factor bidirectional battery charger using SPMC has two operation modes depending on the positive and negative cycle operations.

It is worth noting that it is quite a challenge to work with low-voltage inverters to improve the voltage THD, because, in general, the higher the voltage, the bigger the value of the fundamental component. Moreover, the impact of noises and disturbances is more severe for low-voltage systems than for high-voltage ones. Hence, it should be easy to apply the strategy proposed in this paper to inverters at higher voltage and higher power ratings [7-9].

Mode 1 [positive cycle operation]: During this mode, switches S1a and S4a are turn ON, while it allow current from the battery flow through the switches and flow back to the negative source. The output power P_{o1} is generated during this time as shown in Fig. 8.

Mode 2 [negative cycle operation]: This mode of operation takes a place when S1a and S4a turned OFF. During this time, S2a and S3a are turn ON, to allow current from the battery flow trough it and generate P_{o2} as shown in Fig.8.

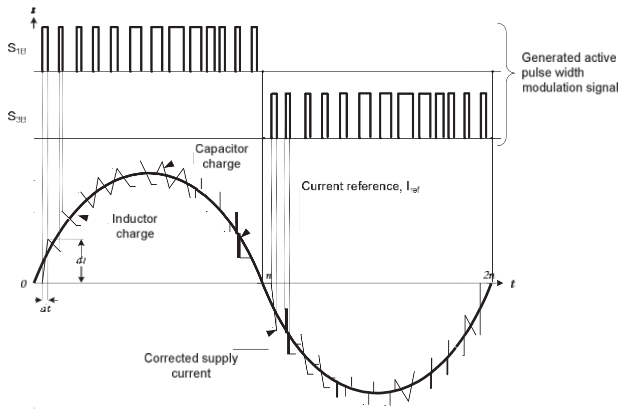

Figure 5 Theoretical Waveforms of the Proposed Unity Power Factor Bidirectional Battery Charger using SPMC

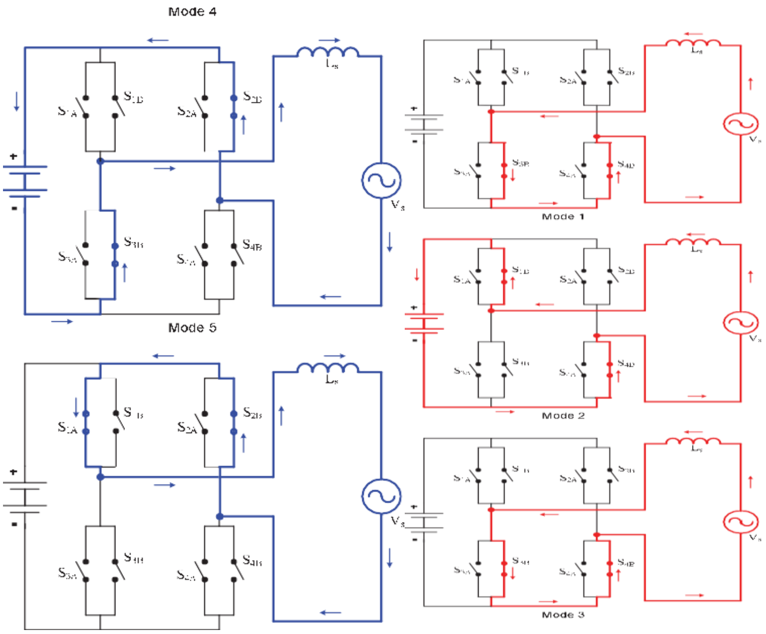

Figure 6 Charging Operational Modes

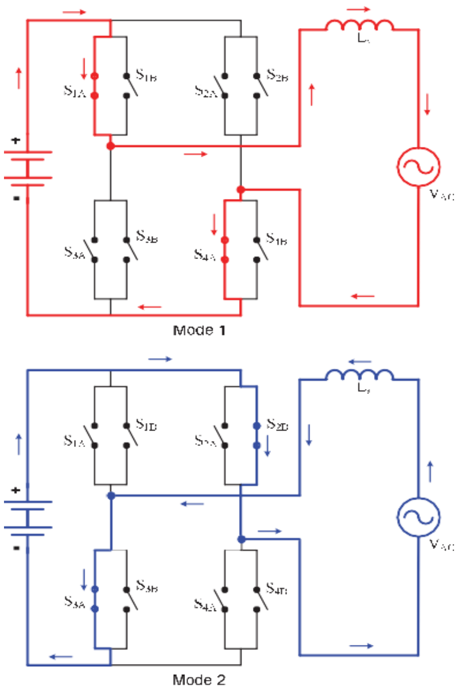

Figure 7 Discharging Operational Modes

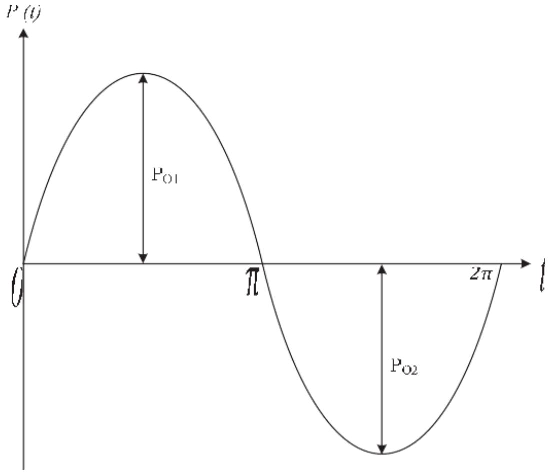

Figure 8 AC Output Power and Its Decomposition

Computer simulation model

The proposed unity power factor bidirectional battery charger system as shown in Fig. 9 to Fig. 12 has been analysed, designed and simulated to validate its overall performance. The simulations have been done using MATLAB/ Simulink to validate the analytical results. The ac supply voltage of the system was chosen to be equal to 26 V, while the dc input voltage is 24 V.

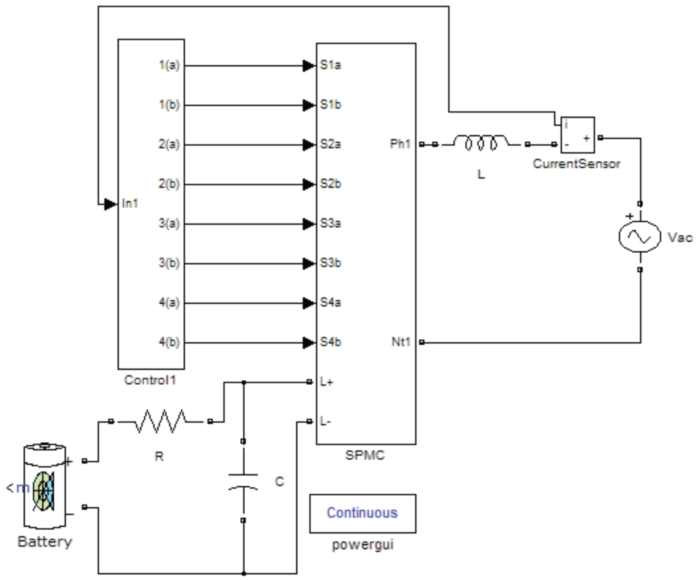

Figure 9 Simulation Model (MLS) Proposed Bidirectional Battery Charger

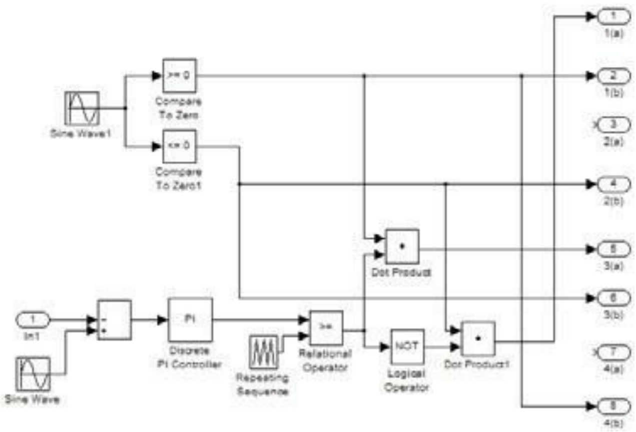

Figure 10 Controller circuit for unity power factor correction

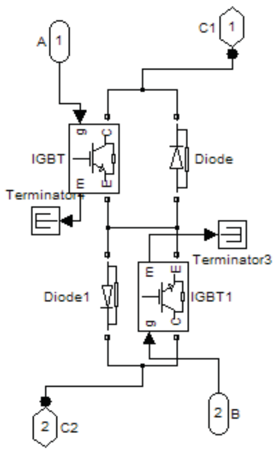

Figure 11 Single-Phase Matrix Converter Model

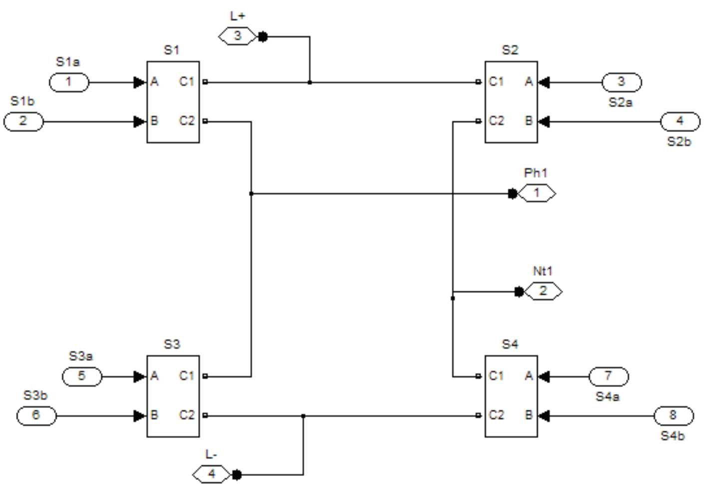

Figure 12 Bidirectional switches

Results and Discussion

The simulation results show the operations of the proposed unity power factor bidirectional battery charger system. In particular, Fig. 14 illustrates the input voltages of the rectifier operation (V_s) and the distorted supply current waveform. Its shows that without incorporating with active power filter function resulted to total harmonics distortion (THD) level up to 262.85%. When incorporating with the active current controller, the previous distorted supply current waveform now becomes continuous, sinusoidal and in phase with the supply voltage waveform as shown in Figure. Then, the power drawn from the battery flow back to the ac source is illustrates in in Figure.

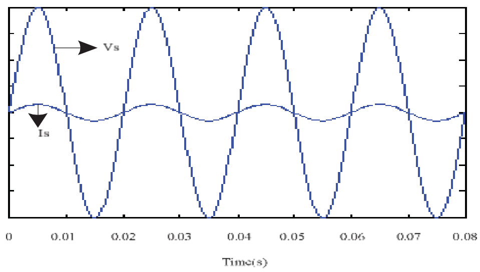

Figure 13 Distorted Supply Current Waveform; THD=262.85%

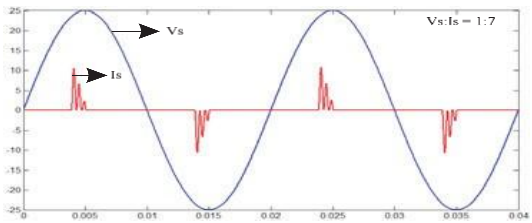

Figure 14 Supply Current and Voltage Waveform; THD=4.7%

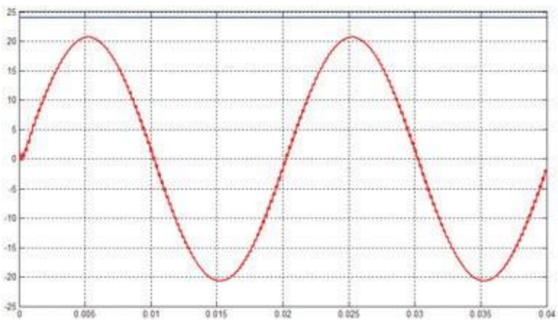

Figure 16 Input and Output Voltage Waveform for DC-AC Operation

Conclusion

A single-phase unity power factor bidirectional battery charger system is proposed in this paper. The simulation results verify the operation characteristics of the proposed system. In summary, the proposed battery charger system has a number of attractive features, such as its capability of fully controllable to perform bidirectional operation by using only a single circuit topology and able to operate in stand-alone as well as in grid- connected mode. Moreover, the proposed battery charger system is able to operate in almost unity power factor.

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