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A novel scheme for charging battery in plug-in hybrid electric vehicles

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ABSTRACT

This paper presents the analysis, design, and implementation of a battery charging three-phase high frequency semi-controlled power converter suitable for plug-in hybrid electric vehicles. The proposed topology has attractive features such as high efficiency; power loss reduction, high power density, and reduced device ratings proportional to the frequency. It also gives economic utilization of grid for unity power factor operation at various conditions and robust. Allowable total harmonic distortion of the generator currents is presented in this topology which can be considered as a minor drawback. For rectifier a hysteresis control algorithm is adopted to achieve lower current harmonic distortion. For converter, the operating principle, control schemes are presented and a dc-dc converter is also used in the rectifier-battery connection. The proposed topology for PHEV applications is experimented on 50-kHz power converter system where the results are promising.

Key Words: Battery control strategy, Plug-in hybrid electric vehicles, Power factor control, Three-phase PWM rectifiers

INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) are becoming popular because it is pollution free. PHEV is a hybrid electric vehicle (HEV) with a very high capacity battery pack that can be recharged by plug-in to the power in a local grid, where the power generation source can be in the form of renewable energy such as wind, solar, etc (H. Oba, 2014). Other than having the environmental benefits and lessening the nation’s dependence on oil, PHEVs also have the potential for providing peak power shaving via V2G (Vehicle to Grid) and powering home in emergency situations via V2H (Vehicle to Home) (Kim, 2009).

Although most of the HEVs currently available on the market are equipped with Ni-MH batteries, the lead-acid batteries are still attractive and used in the mild HEVs, which have relatively restricted functions and cost is high (Anderman, 2012). Studies to improve their performance are being continuously performed, and different viewpoints have arisen providing resolutions other than strictly improving the battery itself (Stienecker, 2006). Further improvement could be achieved when a proper storage device is selectively used corresponding to respective charging status and vehicle driving conditions, which can be called an advanced Hybrid Energy Storage System(HESS) (Spier and Gutmann, 2013). In this paper, a new battery charging topology feasible for PHEV applications is proposed. This topology consists of a three-phase high frequency semi-controlled rectifier and dc-dc converter. Robustness, simplicity, low cost, and high efficiency are inherent characteristics because high frequency and few semiconductor elements are used.

The proposed conversion topology dynamic modeling is explained in Section II. In Section III, PI controller design for maintaining the dc link voltage and hysteresis controller design for the current control is explained. Section IV shows the implementation of hardware and results for the proposed PHEV charging system. Section V is the conclusion part.

The proposed topology: The semi-controlled rectifier structure, which is proposed here, uses three insulated-gate bipolar transistors (IGBT) and three diodes is shown in Fig. 1(a). The main advantages of the proposed topology over the traditional fully-controlled topology are

1) All switches are connected to the same reference in rectifier stage; simplifying the command circuit.
2) Protection; as short-circuit through a leg is not possible.
3) Smaller size; since passive elements are reduced proportionally due to high frequency operation.

Unity power factor (UPF) operation can be achieved.

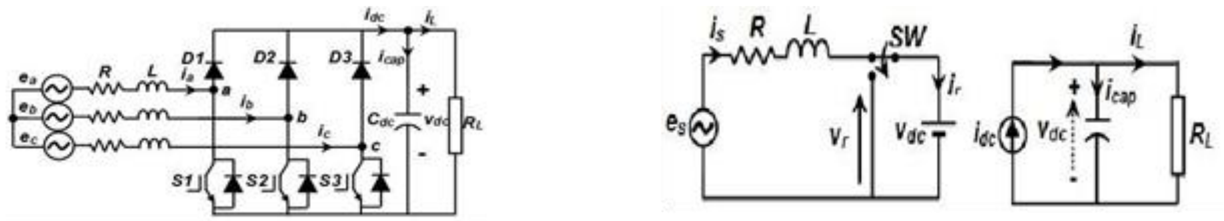


Fig. 1. Ac-dc PWM semi-controlled rectifier. (a) Power circuit, (b) per-phase input equivalent circuit, (c) output equivalent circuit

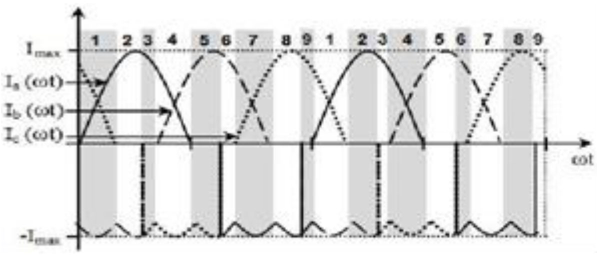
Power transfer operation: The proposed rectifier in Fig. 1 operates as a boost rectifier. When any switch S1, S2, or S3 is turned on then the current will flow through it and respective input inductor current will increase, while respective diode D1, D2, or D3 is reverse biased (off). On the other hand, when S1, S2, or S3 is turned off then the current will flow through the respective diode D1, D2, or D3 (forward biased) and energy will be transferred to dc-bus.

I_a, I_b, and I_c are the phase current representations. For simplification the states are represented as zero (z), forward (f), and reverse current flow (r), resulting in 27 different states as shown in Fig. 3. Only 12 states are physically implemented as shown in Table I. There are three states (10, 11, and 12) will not be implemented for rectification mode of operation; since no power will be transferred to dc-bus. The other nine states can be subdivided into three groups; (1, 4, and 7), (2, 5, and 8), and (3, 6, and 9). Therefore, states 1-3 will be repeated with 4-6 and 7-9. Fig. 4 shows the current waveforms for all rectification possible states 1-9 where only the positive half cycle is modulated while negative half cycle is uncontrolled.

Table.1.Current Flow For Rectifier Operation

	1	2	3	4	5	6	7	8	9	10	11	12
I_a	F	F	f	f	z	r	r	r	z	f	r	r
I_b	F	Z	r	r	r	z	f	f	f	r	f	r
I_c	R	R	z	f	f	f	f	z	r	r	r	f

Fig. 2. Current Waveforms For 9 Rectification States



Bidirectional dc-dc converter: Bidirectional power flow can be obtained with a current-bidirectional two quadrant realization of the switch network. An example is illustrated in Fig. 3, in which a dc-dc converter interfaces batteries to the main dc power bus. The transistors and diodes are connected anti-parallel to form bidirectional switches. Switch S2 is driven with the complement of the S1 drive signal, such that S2 is off when S1 is on, and vice-versa. For battery charging iL(t) is positive and flows through switch S1 and D2. To discharging the current iL(t) is reverses polarity, and flows through S2 and D1. In all aspects, when compared to main dc bus voltage the battery voltage is lower. The magnitude and polarity of the battery current can be controlled via adjustment of the duty cycle D.

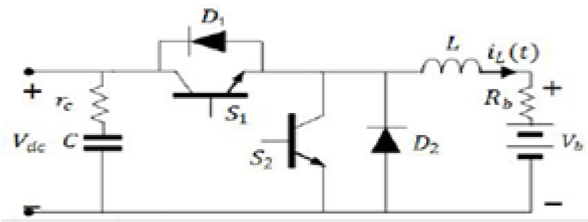


Fig. 3. A buck converter with two-quadrant switches and bidirectional power flow.

To design the control system of a converter circuit, the converter dynamic behavior is essential. Converter dynamic behavior is hampered by the nonlinear time-varying nature of the switching and pulse-width modulation (PWM) process. The model equations are derived below.

The control system:

Rectifier control: Using PI-voltage controller, the dc- voltage can be regulated by choosing the dc-current reference, iref (t) such that,

$$i_{ref}(t) = K^{v}p[V^{r}dc - Vdc(t)] + K^{v}i \int [V^{r}dc - Vdc(t)]dt \quad (1)$$

where $V^{r}dc$ is the desired dc-voltage, $K^{v}p$, $K^{v}i$ are the constant gains of the PI-voltage controller.

Battery control: The primary goal of the battery converter is to regulate the common dc-bus voltage which must be regulated to stay within a stable region regardless of the battery-current variation. To do this, a modified hysteresis-control strategy is applied. The concept of this strategy is to regulate the common dc voltage within a specific band, for example, a hysteresis band. Therefore, the battery charger/discharger is controlled in such a way that the dc-bus voltage should not violate the specified upper and lower limits, Vdc_up and Vdc_ low. For charging and discharging the level of the common dc-bus voltage and the battery buck–booster operates according to the scheme as below

If $Vdc > Vdc\_up$, then charging: $V^{r}dc = Vdc\_up$
If $Vdc < Vdc\_low$, then charging: $V^{r}dc = Vdc\_low$ (2)
If $Vdc\_low \le Vdc \le Vdc\_up$, then no control (rest).

In a power electronic system, there are other circuits such as driver circuit, controller circuit and passive filters which also consume some amount of power. The efficiency of a system (η) can be calculated based on input power (Pin) and total losses (Ploss) as given below

$$\eta = \frac{Pout}{Pin} = \frac{Pin - Ploss}{Pin} = 1 - \frac{Ploss}{Pin}$$

To determine the efficiency of proposed circuit, a loss analysis was performed, considering the developed equations, the semiconductors, and parameters given in Table.2.

Table.2.Semiconductor devices and its parameters

Proposed topology		Fully-controlled topology	
Parameter	**Specification**	**Parameter**	**Specification**
S1-S3,D1-D3	SKM50GAL125D	S1-S6	SKM50GB125D
Vswitch	1200V	Vswitch	1200V
Iswitch	50A	Iswitch	50A
Power rating	60 kW	Power rating	60 kW

Fig. 4 compares the estimated efficiency of the proposed rectifier stage (η_1) with the fullycontrolled rectifier topology (η_2). In the fully controlled bridge structure, the currents can be modulated in both half cycles which leads to less input current harmonic distortion when compared to the proposed half controlled bridge topology. Since it has larger switching losses and it requires the use of bootstrap integrated circuits.

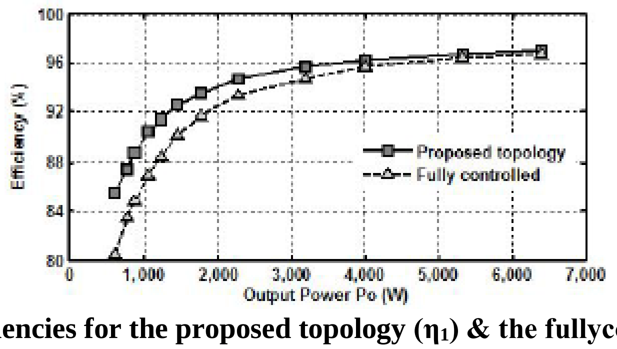


Fig. 4.Estimated efficiencies for the proposed topology (η_1) & the fullycontrolled topology (η_2)

EXPERIMENTAL RESULTS

A 60-kW prototype of the proposed battery charging high frequency power converter was developed. Fig. 6 shows the prototype schematic diagram of hardware implementation. The high frequency power converter module has been designed and implemented in the energy systems research laboratory (ESRL). It is composed of a semi-controlled rectifier and a bidirectional dc-dc converter. The individual converters are controlled by their own TMS320F28335-based control platforms. The specifications and parameters used in the prototype are shown in Tables.3. and 4.

Table.3.Rectifier specifications and parameters

Parameter	Specification
Input voltage range	70-208 Vrms
Line input inductor (L1)	0.3mH
Inductor internal resistance	0.012 W
DC-bus capacitor (Cdc)	1000µf
DC-bus voltage (Vdc)	400 V
Switching frequency (fsw)	30-45 kHz

Table.4.Battery and DC-Dc converter specifications & parameters

Parameter	Specification	Parameter	Specification
Vdc	400 V	Rated voltage	160 V
L2	0.15mH	Connection	10-series
Switch	IGBT	Rated capacity	100 AH
Fsw	50kHz	Battery type	Lead-acid
Control	Bulk/absorption float	Total power	12kW

Rectifier performance: Fig. 6(a) shows the dc-bus voltage, the current through phase "a," and the respective grid phase voltage. The dc-bus voltage has no overshoot and low voltage ripple of 2.3%. Fig. 6(b) shows the harmonic spectrum of the grid voltage (THD=0.37%) and rectifier current (THD=17.03%), where the 2nd, 3rd, and 5th order components are the most relevant. UPF operation was investigated (PF=0.991); since the rectifier current and the phase voltage are in phase. This improvement in the power factor represents more economic utilization of grid power.

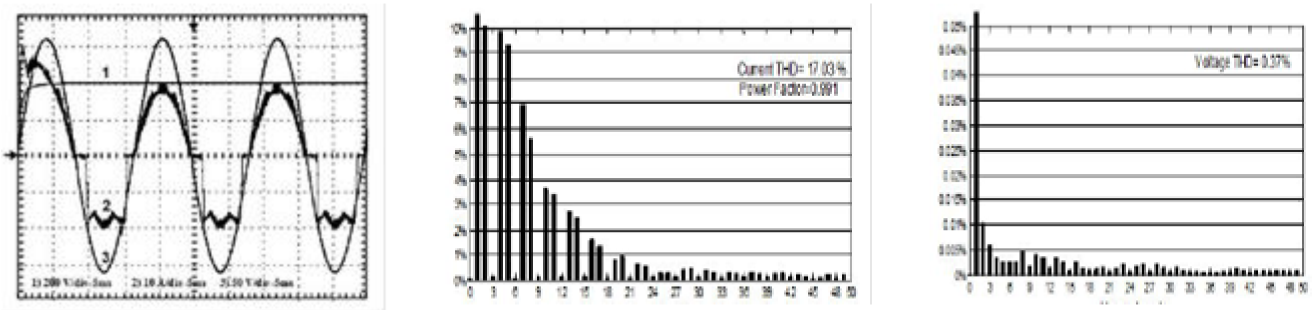


Fig. 6(a). DC-bus output voltage (1-200 V), rectifier current (2-10 A), and grid voltage (3-50 V) for phase "a". (b) Harmonic spectrum of generator voltage (c) the input current

DC reference change test: Fig. 7 shows the reference voltage, V^{r}dc and the actual voltage, Vdc under dc-bus voltage reference change. The main objective of this test is to investigate the control system performance under dc-bus voltage level change to large values for medium-voltage distribution applications. The dc-bus is connected to a 3-hp dc-motor operated at full load. A reference step change is applied and set to be increased from 400 V to 500 V. The corresponding rectifier current at rated power (2.5 kW) is also shown in Fig. 8. According to gain parameters design, it is noticed that the control operation has over damped transient response and there is no overshoot. Therefore, the overall dynamic performance has been greatly improved.

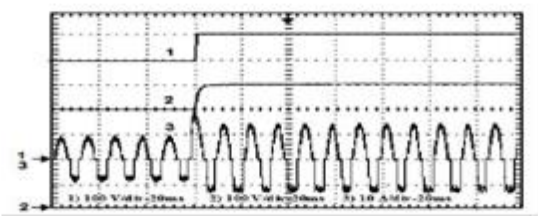


Fig. 7. The reference and actual dc-bus voltage (1, 2-100 V) & rectifier current (3-10 A)

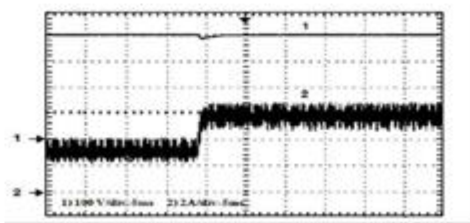


Fig. 8. DC-bus o/p voltage (1-100 V) & load current (2A).

CONCLUSION

In this paper, a new battery charging high frequency power converter module was developed for PHEV systems. The proposed three-phase semi-controlled rectification topology reduces the switching and conduction losses when compared to fully-controlled topology. A UPF operation (0.981) was achieved for better economic utilization of the grid absorbed power. The high efficiency operation was verified due to reduced number of switches (average 95%). A second order SPLL was accurately designed for accurately detecting the phase angle during presence of the 5th and 7th harmonics. A fast control dynamic response was achieved (0.1 second) under different possible conditions; dc-reference step change and load variation. All the obtained results confirm the effectiveness of the proposed system for PHEV application.

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