CURRENT DRIVEN ZVZCS FULL-BRIDGE DC/DC CONVERTER FOR ELECTRIC VEHICLE BATTERY CHARGING

[1]ANUPAMA. P. K, M., [2]REENA. R. RAJAN

[1]Tech student, Nehru College of Engineering & Research Centre Trissur
[2]Asst. Professor, EEE Dept. Nehru College of Engineering & Research Centre, Trissur
Email: anupamasubink@gmail.com, reenasbc@gmail.com

Abstract— DC/DC converter is part of a plug-in AC/DC converter used to charge the traction battery in an electric vehicle. The conventional topologies failed to operate the converter with zero current and zero voltage switching during no load condition resulting high voltage spikes in the output voltage. In order to confirm reliable operation of the full-bridge converter under wide load variations, the converter should not only operate with soft-switching from no-load to full-load condition, but also from full-load to no-load condition making full range of operation. For achieving such stringent requirements and high reliability, the converter employs a symmetric passive way near lossless auxiliary circuit to provide the reactive current for the full-bridge semiconductor switches, which guarantees zero voltage switching at turn-on times for all load conditions. This is a current driven topology in combination with a voltage multiplier in order to clamp the output voltage and also satisfy ZVZCS operation of the converter resulting in high voltage gain for all load conditions.

Keywords—DC/DC converter, full-bridge converter, lagging leg, leading leg, snubber capacitor, Zero Current Switching (ZCS), Zero Voltage Switching (ZVS), Zero Voltage Zero Current Switching (ZVZCS) , Current Driven Zero Voltage Zero Current Switching(CD ZVZCS).

I. INTRODUCTION

P OWER conversion systems in electric vehicles (EVs) usually use a high energy battery pack to store energy for the electric traction system. Energy conversion during the battery charging is performed by an AC/DC converter. Such AC/DC converters, which are used to charge the high-energy battery, usually consist of two stages: input power factor correction (PFC) for AC/DC conversion and DC/DC conversion for battery charging. PFC is used to improve the quality of the input current, which is drawn from the utility, and the charger which is an isolated DC/DC converter, is used to charge the high voltage battery and provide galvanic isolation between the utility mains and the traction battery.

Full-bridge topology is the most popular topology used in the power range of a few kilowatts (1–5 KW) for DC/DC converters. Since the switch ratings are optimized for the full-bridge topology, this topology is extensively used in industrial applications. High efficiency, high power density, and high reliability are the prominent features of this topology. In Section II a review of common EV power conversion system are done. Conventional full-bridge DC-DC converter topology is presented in Section III. Novel Current Driven ZVZCS DC-DC converter and its various operating modes with waveforms are described in Section IV. Design and simulation of conventional converter and CD ZVZCS converter is given in section V. In section VI simulation results of both converters are given.

II. EV POWER CONVERSION SYSTEM

The power conversion system consists of an ac/dc converter, a three-phase dc/ac inverter, and a dc/dc converter. The ac/dc converter is a plug-in converter, which charges the high-voltage battery. The high-voltage battery is supplying power to the three-phase inverter which feeds the three-phase motor. The high-voltage battery is also charging the 12V battery through a dc/dc converter. Fig.1 shows the block diagram of EV power conversion system.

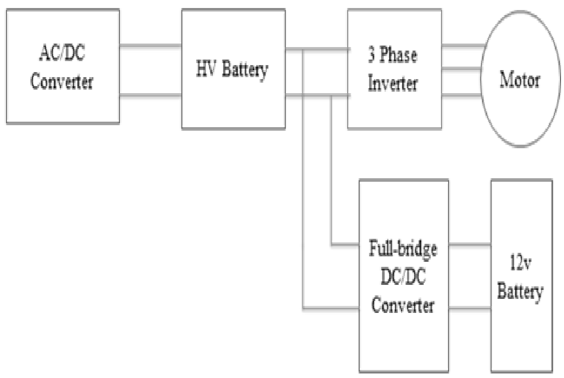

Fig.1. EV Power Conversion System

Different system structures, both bidirectional and unidirectional, are being used for the EV power conditioning system. In this system, there are two battery units: a high voltage battery, which feeds the inverter and the electric motor, and a 12V battery. The power switching devices, electric motors plays an important role in introducing the hybrid vehicles and fuel cell vehicles in market. The power electronic system should be efficient to improve the range of the electric vehicles and fuel economy in hybrid vehicles. The selection of power semiconductor devices, converters/inverters, control and switching strategies, the packaging are very crucial to the development of efficient and high-performance vehicles.

III. CONVENTIONAL SYSTEM

Full-bridge dc/dc converters are extensively applied in medium to high power dc/dc power conversion. For power levels up to 3 kW, the full-bridge converters now employ MOSFET switches and use Phase-Shift Modulation (PSM) to regulate the output voltage. In most of these converters, zero voltage switching (ZVS) is achieved by placing a snubber capacitor across each of the switches and either by inserting an inductor in series with the transformer or by inserting an inductor in parallel to the power transformer. In a practical full-bridge configuration, the snubber capacitor may be the internal drain-to-source capacitor of the MOSFET, the series inductor may be the leakage inductor and the parallel inductor may be the magnetizing inductor of the power transformer. This makes the power circuit of these converters very simple. However, the full-bridge converter with the series inductor loses its ZVS capability at no-load (or light-load), and the converter with the parallel inductor loses its ZVS under short-circuit. Loss of ZVS implies extremely high switching losses at high switching frequencies and very high EMI due to the high di/dt of the snubber discharge current. Loss of ZVS can also cause a very noisy control circuit, which leads to shoot-through and loss of the semiconductor switches. The ZVS range can be extended by increasing the series inductance. However, having a large series inductance limits the power transfer capability of the converter and reduces the effective duty ratio of the converter.

When the battery is charged, the load is absolutely zero and the converter should be able to safely operate under the zero load condition. Since ZVS in conventional full-bridge PWM converters is achieved by utilizing the energy stored in the leakage inductance to discharge the output capacitance of the MOSFETs, the range of the ZVS operation is highly dependent on the load and the transformer leakage inductance. Thus, this converter is not able to ensure ZVS operation for a wide range of load variations.

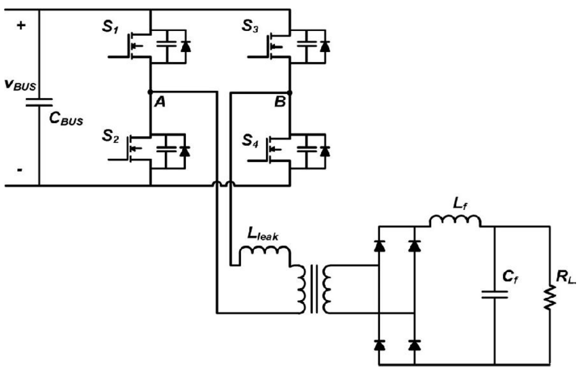

Fig.2. Conventional Full-Bridge Converter

A fundamental problem related to the conventional full-bridge phase-shift DC/DC converter is the voltage spikes across the output diodes. Fig. 2 shows the schematic of the conventional full-bridge converter. Basically, the leakage inductance of the transformer causes the voltage spikes across the output diodes. Theses spikes are intensified by increasing the switching frequency of the converter. Thus, the diodes should be designed overrated to be able to withstand the voltage spikes, which leads to higher losses due to the higher forward voltage drop of the diodes and poorer reverse recovery characteristics. In addition, the spikes significantly increase the EMI noise of the converter. This fact makes the topology not very practical for high frequency, high voltage applications. There are quite a few references that proposed solutions for the voltage spikes across the output diodes. Some references tried to decrease the leakage inductance as much as possible though the transformer winding structures, which effectively decreases the peak of the voltage spikes across the output diodes. However, reducing the leakage inductance decreases the ZVS operating range of the full-bridge converter, which results in a very narrow range of ZVS operation.

The problem of voltage spikes is essentially related to the voltage-driven output rectifiers. This is due to the fact that the full-bridge inverter produces high frequency voltage pulses across the output diode rectifier, which is connected to the output inductor as shown in Fig. 2. The voltage-driven rectifier works perfectly if there is no leakage inductance in between the output of the full-bridge inverter and the diode rectifier. However, the existence of the leakage inductance makes the rectifier connect two current sources, i.e., leakage inductance and output inductance, together. This connection creates high voltage spikes across the output diodes. In this paper, a new topology is proposed based on a current driven rectifier, which effectively rectifies the voltage stress problems related to the full-bridge DC/DC converter. The proposed topology provides zero current switching (ZCS) for the output rectifiers, which eliminates reverse recovery losses of the output diode rectifiers .

IV. CURRENT DRIVEN ZVZCS DC/DC CONVERTER

The main problem regarding the conventional full-bridge converter is the series connection of the leakage inductor and output inductor through the diode rectifier. The current driven ZVZCS DC/DC full-bridge converter system is based on a current driven rectifier, which effectively rectifies the voltage stress problems related to the full-bridge DC/DC converter. This topology provides zero current switching (ZCS) for the output rectifiers, which eliminates reverse recovery losses of the output diode rectifiers. In this topology, the full-bridge inverter converts the DC-bus voltage to a high frequency quasi-square wave voltage. Then there is an inductor in series with the transformer, which acts as a current source for a current driven rectifier. The current driven rectifier rectifies the output current of the transformer and transfers power to the output. Fig. 2 shows the current driven ZVZCS DC-DC converter. The converter provides the full range of operation giving ZVS from no-load to full-load condition. The converter requires same amount of reactive current for both leading and lagging legs. This is due to the fact that the series inductor current starts from zero during the switching of the leading leg MOSFETs, the auxiliary circuit must only provide just enough reactive current to charge and discharge the leading leg MOSFET output capacitors. Therefore, both the auxiliary inductors only carry small amounts of current, just enough for the ZVS turn–ON of the MOSFETs. Therefore, the two auxiliary circuits are symmetric and, hence, easier to manufacture.

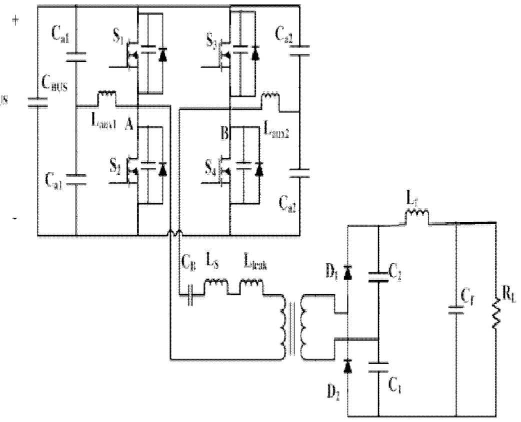

Fig. 4. Proposed Converter

In this topology, the voltage spikes across the output diodes are eliminated by using a current-driven configuration, which is realized by a series inductance with the main power transformer operating in discontinuous mode ensuring complete energy transfer and a capacitive filter at the output of the diode bridge. The series inductor acts as a current source and the capacitive filter clamps the voltage across the diode bridge. In one switching cycle, the circuit has 14 modes during steady-state operation. Due to the symmetrical structure, the analysis is only given for half a switching cycle. In half cycle, the steady state behavior of the circuit is divided into the following operating modes:

Mode I :($t_o \leq t \leq t_1$) : At t_0 , S_2 is turned OFF. The output capacitor of S_1 is discharging and that of S_2 is charging up with the reactive current provided by the auxiliary circuit. During this interval, the secondary-side diodes are reversed biased and are OFF. Therefore, the rising voltage V_{AB} conducts a very small current through the DC blocking capacitor C_b, series inductance L_s , leakage inductance L_{leak} , and magnetizing inductance L_M . Fig. 6(a) shows the active components in this mode of operation.

Mode II :($t_1 \leq t \leq t_2$) : This mode starts once the output diodes get forward biased. Here, the output capacitor of the MOSFET, S_1 is still discharging to finally reach zero and that of S_2 is charging up to V_{dc}. This mode ends once the voltage across this capacitor becomes zero. This interval ends once the output capacitor of the MOSFET S_1 has discharged completely. Fig 6 (b) shows the active components in this mode of operation

Mode III :($t_2 \leq t \leq t_3$) : This mode starts once the MOSFET output capacitors have been charged and discharged completely. During this mode, the output diodes clamp the secondary voltage to the output voltage. The capacitor C_1 on secondary side charges through D_1. Thus, there is a constant voltage across the combination of the series inductance and the leakage inductance. Therefore, the series current ramps up to its peak value. This mode ends once the MOSFET S_4, gate voltage becomes zero. Fig 6(c) shows the active components in this mode.

Mode IV :($t_3 \leq t \leq t_4$) : Output capacitor of S_3 is discharging from and that of S_4 is charging up to V_{dc}. This mode ends when output capacitor of S_3 completely discharge and S4 output capacitor got charged to V_{dc}. Therefore the current on secondary side ramps down. During this mode the body diode of S_3 is conducting. This mode finishes once the gate pulse of S_3 is applied and the current flows through MOSFET channel. Fig 6(d) shows the active components in this mode.

Mode V :($t_4 \leq t \leq t_5$) : This mode commences when V_{AB} is zero. Then the output voltage of inverter is zero and the output diode clamps the secondary voltage to the output voltage. The negative voltage will be incident across L_{series} which is the reflected output voltage at the transformer primary side. Fig 6(e) shows the active components in this mode of operation.

Mode VI :($t_5 \leq t \leq t_6$) : This mode starts when the gate pulse is applied to S_3. This mode is same as that of mode V except S_3 channel is conducting rather than the body diode of S_3. During the end of this mode current through L_{series} is ramping down to zero. S_1 turns OFF near zero current switching at the end of this mode. Therefore at the end of this mode the diode turn off with zero current. Active components are shown in fig 6(f).

Mode VII :($t_6 \leq t \leq t_7$) : This interval starts once current through output diodes reaches zero and the diode turn off naturally with zero current. The capacitor C_f feeds the output load with stored energy while on the transformer primary side there is no current. Active components are shown in fig 6(g).

Waveforms for the different modes of operation are shown in fig.5.

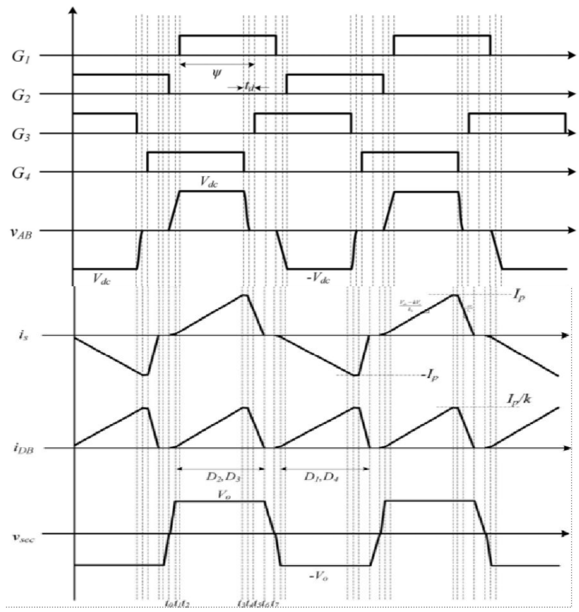

Fig.5. Ideal Waveforms of the Converter.

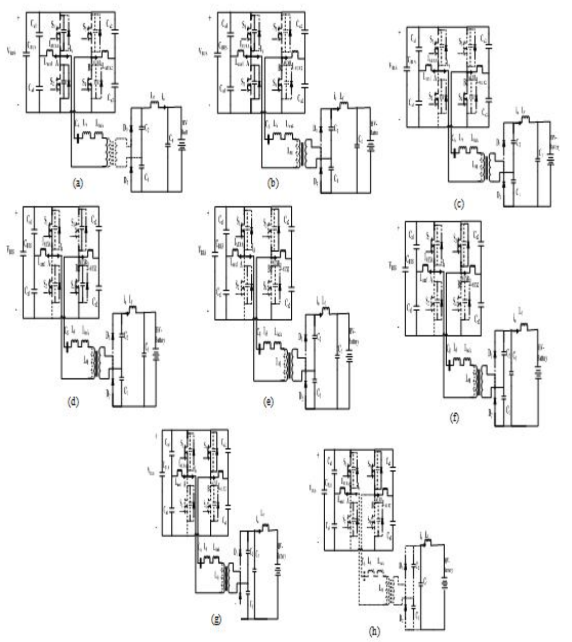

Fig. 6. (a) Active Components of Mode I. (b) Active Components of Mode II. (c) Active Components of Mode III. (d) Active Components of Mode IV. (e) Active Components of Mode V. (f) Active Components of Mode VI. (g) Active Components of Mode VII

V. DESIGN AND SIMULATIONS

A. Design of Auxiliary Inductors

Auxiliary inductors are designed based on the amount of reactive power required to guarantee ZVS for the MOSFETs. The reactive current should be enough to charge and discharge the MOSFET output capacitors. In, the design procedure of auxiliary circuits for a regular full-bridge converter is explained. The auxiliary circuit current is constant during the dead time, the inductor act as a constant current source, which discharges the capacitor across S_1 and charges the capacitor across S_2. The value of this constant current source is

$$I_{PA} = \frac{V_{DC}}{8L_{AUX1}f_S} \qquad (1)$$

The value of auxiliary inductor is designed as

$$L_{AUX1} = \frac{1}{128C_{S0}f_S^2} \qquad (2)$$

C_{s0} = Switch output Capacitor
f_s = Switching frequency

B. Design of Series Inductor

The reflected output current at the primary side is half of the peak current in the series inductor. Therefore, the value of series inductance is given by

$$L_{seq} = \left(1 + k\frac{V_0}{V_{DC}}\right)\frac{V_0^2}{P_{0,max}}\frac{T_S}{64} \qquad (3)$$

where $L_{seq} = L_s + L_{leak}$

C. Design of Output Capacitor

The value of the capacitor is designed by

$$C_f = \frac{I_0}{8f_s\Delta V_{cf}} \qquad (4)$$

ΔV_{cf} - 5-10% of output voltage

TABLE I
SIMULATION PARAMETERS OF CONVENTIONAL FULL-BRIDGE CONVERTER

Input Voltage	230V
Auxiliary Inductor A	33µH
Auxiliary Inductor B	67µH
Output capacitor	140µF
Filter Inductor	80µH
Transformer Turn's Ratio	1:1.18
Auxiliary Capacitor	2.2µF
Output Voltage	494V

TABLE II
SIMULATION PARAMETERS OF CD ZVZCS DC/DC CONVERTER

Input Voltage	230V
Output Voltage	794 V
Auxiliary Inductor	$67*10^{-3}$H
Auxiliary Capacitor	$2.2*10^{-5}$F
Switching Frequency	50 KHz
Filter Capacitor	0.1µF
Filter Inductor	1µH

VI. SIMULATION RESULTS

The conventional ZVZCS DC-DC Converter and CD ZVZCS full-bridge DC-DC converter simulated using MATLAB/SIMULINK and the waveforms are shown below.

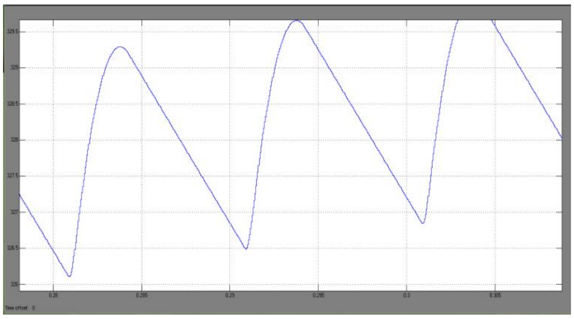

Fig.9. Output voltage waveform of conventional full bridge converter at no-load condition.

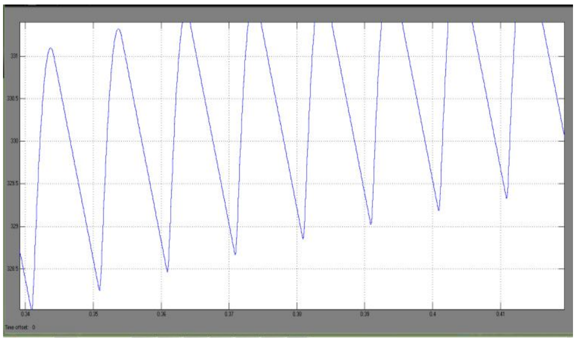

Fig.10. Output voltage waveform of the conventional full-bridge converter at full-load condition.

Fig.9 shows that the output voltage contained voltage spikes with it for the conventional converter at no-load condition. Fig.10 shows that while varying the load from full-load condition to no-load condition the output voltages is not maintained as constant and are accompanied with large voltage spikes.

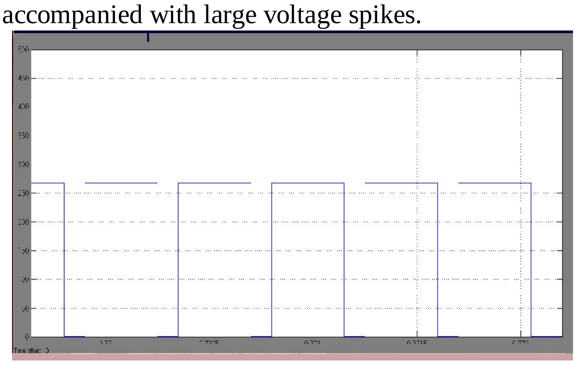

Fig.11. Converter output voltage waveform of CDZVZCS DC-DC converter at full-load condition.

Fig.11 shows the output waveforms of Current Driven ZVZCS DC/DC converter at no-load condition. The output voltage is free from voltage spikes appeared on the secondary side of transformer. Active clamping of these voltage spikes are done by using a current driven rectifier on the secondary side of transformer. The output diode bridge clamps voltage spike to the output voltage. The system is load independent . Therefore by varying the load from full-load to no-load the voltage is maintained as almost constant.

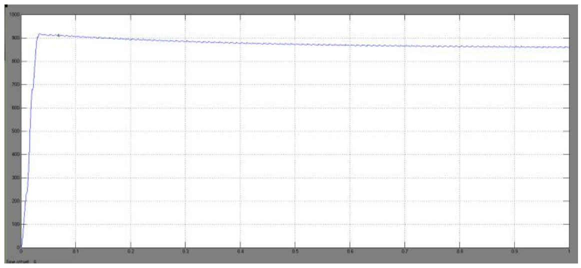

Fig.12 Output voltage waveform of CDZVZCS converter at full-load condition.

Fig.12 shows the converter output waveforms at full-load condition. According to this figure, the converter is able to operate without any adverse voltage spikes across any of the semiconductors. The voltage multiplier gives the output voltage as integral multiples of input voltage. The output obtained was 794V for an input of 230V.Therefore the voltage gain was almost three times compared to the conventional converter. In practical applications we can extend the voltage multiplier cells to any number of stages according to the required voltage.

CONCLUSIONS

The conventional ZVZCS DC-DC converter and Current Driven ZVZCS DC-DC converter were simulated using MATLAB/SIMULINK. The CD ZVZCS full-bridge topology eliminates the adverse effects of the voltage spikes at the secondary side of the transformer, as well as the freewheeling mode of operation. The output voltage was nearly four times the input voltage increasing the voltage gain of the converter. It was found that the converter has superior performance over the conventional converter especially in regards to the voltage across the secondary-side diode-bridge providing the load independent output. The topology can be combined with a solar input for future expansion.

REFERENCES

[1] Majid Pahlevaninezhad, Pritam Das, Josef Drobnik, Praveen K.Jain, and Alireza Bakhshai,“A Novel ZVZCS Full-Bridge DC/DC Converter Used for Electric Vehicles,” IEEE Trans.power electron., vol.27, no.6, June 2012.

[2] M. Pahlevaninezhad, J. Drobnik, P. Jain, and A. Bakhshai, “A load adaptive control approach for a zero voltage switching DC/DC converter used for electric vehicles,” IEEE Trans. Ind. Electron., vol.59, no.2, pp.920-933, Feb.2011.

[3] Ahmed Yousuf Saber, and Ganesh Kumar Venayagamoorthy, “Plug-in vehicles and renewable energy sources for cost and emission reductions,” IEEE Trans. Ind. Electron., vol. 58, no. 4, pp. 1229–1238, Apr. 2011.

[4] M. H. Rashid “Power Electronics,” third edition pp- 190-250

[5] W. Xinke, J. Zhang, X. Xie, and Z. Qian, “Analysis and optimal design considerations for an improved full bridge ZVS DC-DC converter with high efficiency,” IEEE Trans. Power Electron., vol. 21, no. 5, pp. 1225–1234, Sep. 2006

[6] B. M Hasaneen, and A.Elbaset Mohammed, “Design and simulation of DC/DC boost converter,” IEEE Trans.ind.Electron, pp-335-340

[7] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, “Energy storage systems for automotive applications,” IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2258–2267, Jun. 2008.

[8] A. Emadi, Y. J. Lee, and K. Rajashekara, “Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles,” IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2237–2245, Jun. 2008.

★★★