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Simulation Of Bidirectional Dc-Dc Converter For Hybrid Battery Vehicles

S. KARTHEEK
PG Scholar, Department of EEE
G.K.C.E, Sullurpet, Andhrapradesh, INDIA.

M. SRINATH
Assistant Professor, Department of EEE
G.K.C.E, Sullurpet, Andhrapradesh, INDIA.

Abstract: **This paper presents modeling, design and analysis of a bidirectional half-bridge DC/DC converter suitable for power electronic interface between the main energy storage system and the electric traction drive in hybrid electric vehicles. A hybrid energy storage system composed of a battery unit and an ultra-capacitor pack is considered. A parallel dc-linked multi input converter with a half-bridge bidirectional DC/DC cell topology is chosen to link the battery/ultra capacitor storage unit with the dc-link. The paper focuses on modeling the proposed converter for both dynamic and steady state analysis. Averaging and linearization techniques are applied to obtain the averaged state space models and small signal models of the converter in both boost and buck operation modes. A criterion for sizing the converter passive components based on the imposed design specifications and constraints is illustrated. Simulation results of the buck-boost converter during normal functioning and under faulty conditions are presented. In particular, short-circuit faults and open-circuit faults of diodes and transistors are analyzed.**

I. INTRODUCTION

The use of DC/DC converters is essential in hybrid vehicles. Mainly, there exist two types of DC/DC converters on board of a Hybrid Electric Vehicle (HEV). The first is a low power bidirectional DC/DC converter which connects the high voltage dc-link with a low voltage battery used to supply low power loads. The second is a high power bidirectional DC/DC Converter used to connect the main energy storage unit with the electric traction drive system. This paper presents modeling, design and analysis of the later converter. A Hybrid Energy Storage System (HESS) composed of a battery unit and an Ultra-Capacitor (UC) pack is considered. Based on the study done, a parallel dc-linked multi-input converter with half-bridge bidirectional DC/DC cells is chosen to link the battery/UC storage unit with the dc-link. The DC/DC converter is used to provide a regulated dc voltage at higher level to the inverter and to control power flow to and from the electric drive during motoring and generating modes respectively. The paper mainly focuses on modeling the proposed converter for both dynamic and steady state analysis. Section II describes the electric drive train specifications. In Section III, averaging and linearization techniques are applied to the DC/DC converter state space model for both boost and buck operation modes. A criterion for sizing the converter passive components based on the imposed design constraints is presented. Presents simulation results of the chosen converters using Matlab/Simulink. The operation of the buck-boost converter is illustrated during normal functioning and under faulty conditions resulting from power switching device faults.

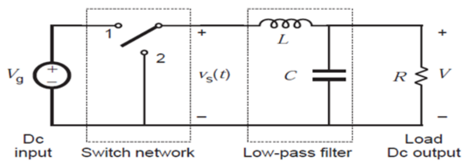
In particular, Short-Circuit (SC) and Open-Circuit (OC) faults of diodes and transistors are analyzed. A single fault is carried at a time; leading to eight different fault operation modes.

II. DC-DC POWER CONVERTERS

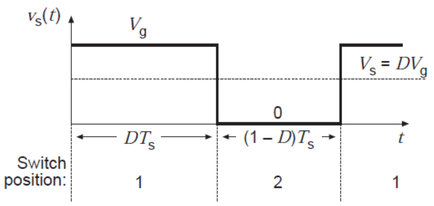
Dc-dc power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, as well as dc motor drives. The input to a dc-dc converter is an unregulated dc voltage Vg. The converter produces a regulated output voltage V, having a magnitude (and possibly polarity) that differs from Vg. For example, in a computer off-line power supply, the 120 V or 240 V ac utility voltage is rectified, producing a dc voltage of approximately 170 V or 340 V, respectively. A dc-dc converter then reduces the voltage to the regulated 5 V or 3.3 V required by the processor ICs.

High efficiency is invariably required, since cooling of inefficient power converters is difficult and expensive. The ideal dc-dc converter exhibits 100% efficiency; in practice, efficiencies of 70% to 95% are typically obtained. This is achieved using *switched-mode*, or *chopper*, circuits whose elements dissipate negligible power. *Pulse-width modulation* (PWM) allows control and regulation of the total output voltage. This approach is also employed in applications involving alternating current, including high efficiency dc-ac power converters (inverters and power amplifiers), ac-ac power converters, and some ac-dc power converters (low-harmonic rectifiers).

A basic dc-dc converter circuit known as the *buck converter* is illustrated in Fig. 1. A single-pole double-throw (SPDT) switch is connected to the dc input voltage *V*g as shown. The switch output voltage *v*s(*t*) is equal to *V*g when the switch is in position 1, and is equal to zero when the switch is in position 2. The switch position is varies periodically, such that $v_s(t)$ is a rectangular waveform having period T_s and duty cycle D. The duty cycle is equal to the fraction of time that the switch is connected in position 1, and hence $0 < D < 1$. The *switching frequency* f_s is equal to $1/T_s$. In practice, the SPDT switch is realized using semiconductor devices such as diodes, power MOSFETs, IGBTs, BJTs, or thyristors. Typical switching frequencies lie in the range 1 kHz to 1 MHz, depending on the speed of the semiconductor devices.



buck converter consists of a switch network that reduces the dc component of voltage, and a low-pass filter that removes the high-frequency switching harmonics



switch voltage waveform

$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt = DV_g$$

The integral is equal to the area under the waveform, or the height V_g multiplied by the time DT_s. It can be seen that the switch network reduces the dc component of the voltage by a factor equal to the duty cycle D. Since $0 < D < 1$, the dc component of V_s is less than or equal to V_g.

The power dissipated by the switch network is ideally equal to zero. When the switch contacts are closed, then the voltage across the contacts is equal to zero and hence the power dissipation is zero. When the switch contacts are open, then there is zero current and the power dissipation is again equal to zero.

Therefore, the ideal switch network is able to change the dc component of voltage without dissipation of power. In addition to the desired dc voltage component V_s, the switch waveform $v_s(t)$ also contains undesired harmonics of the switching frequency. In most applications, these harmonics must be removed, such that the converter output voltage $v(t)$ is essentially equal to the dc component $V = V_s$. A low-pass filter is employed for this purpose. The converter of Fig. 1 contains a single-section L-C low-pass filter. The filter has corner frequency f_0 given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

The corner frequency f_0 is chosen to be sufficiently less than the switching frequency f_s, so that the filteressentially passes only the dc component of $v_s(t)$. To the extent that the inductor and capacitor are ideal, the filter removes the switching harmonics without dissipation of power. Thus, the converter produces a dc output voltage whose magnitude is controllable via the duty cycle D, using circuit elements that (ideally) do not dissipate power.

The *conversion ratio* $M(D)$ is defined as the ratio of the dc output voltage V to the dc input voltage V_g under steady-state conditions:

$$M(D) = \frac{V}{V_g} \qquad (3)$$

For the buck converter, $M(D)$ is given by

$$M(D) = D \qquad (4)$$

This equation is plotted in Fig. 2. It can be seen that the dc output voltage V is controllable between 0 and V_g, by adjustment of the duty cycle D.

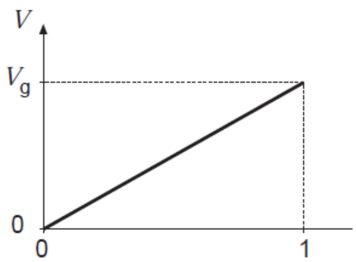


Figure 2. Buck converter dc output voltage V vs. duty cycle D.

Figure 3 illustrates one way to realize the switch network in the buck converter, using a power MOSFET and diode. A gate drive circuit switches the MOSFET between the conducting (on) and blocking (off) states, as commanded by a logic signal del(t). When del(t) is high (for $0 < t < DT_s$), then MOSFET $Q1$ conducts with negligible drain-to-source voltage. Hence, $v_s(t)$ is approximately equal to V_g, and the diode is reverse-biased. The positive inductor current $i_L(t)$ flows through the MOSFET. At time $t = DT_s$, (t) becomes low, commanding MOSFET $Q1$ to turn off. The inductor current must continue to flow; hence, $i_L(t)$ forward-biases diode $D1$,and $v_s(t)$ is now approximately equal to zero. Provided that the inductor current $i_L(t)$ remains positive, then diode $D1$ conducts for the remainder of the switching period. Diodes that operate in the manner are called *freewheeling diodes*.

Since the converter output voltage *v*(*t*) is a function of the switch duty cycle *D*, a control system can be constructed that varies the duty cycle to cause the output voltage to follow a given reference *v*r. Figure 3 illustrates the block diagram of a simple converter feedback system. The output voltage is sensed using a voltage divider, and is compared with an accurate dc reference voltage *v*r. The resulting error signal is passed through an op-amp compensation network. The analog voltage *v*c(*t*) is next fed into a *pulse-width modulator*. The modulator produces a switched voltage waveform that controls the gate of the power MOSFET *Q*1. The duty cycle *D* of this waveform is proportional to the control voltage *v*c(*t*). If this control system is well designed, then the duty cycle is automatically adjusted such that the converter output voltage *v* follows the reference voltage *v*r, and is essentially independent of variations in *v*g or load current.

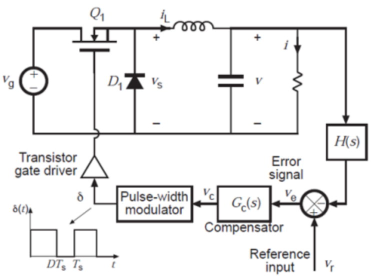


Figure 3. Realization of the ideal SPDT switch using a transistor and freewheeling diode. In addition, a feedback loop is added for regulation of the output voltage.

III. ELECTRIC TRACTION SYSTEM SPECIFICATIONS

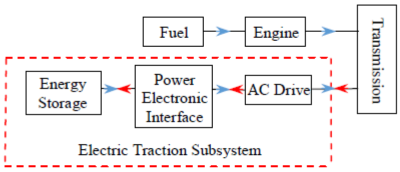
When designing a bidirectional DC/DC converter suitable for Power Electronic Interface (PEI) between the Energy Storage System (ESS) and the electric traction drive, it is important to indicate the specifications of the electric traction system. These specifications include identifying the level of hybridization of the vehicle; as well as the choice of hybrid drive train configuration, HESS, electric AC drive system, and DC/DC PEI configuration.

IV. LEVEL OF HYBRIDIZATION

In order to determine the dc-link voltage and the energy storage unit capacity at the DC/DC converter terminals, it is empirical to specify the vehicle hybridization level. A full HEV is chosen with large traction motor, high-capacity energy storage pack and main DC bus voltage around 200-300V.

B. CHOICE OF HYBRID DRIVETRAIN CONFIGURATION

A parallel hybrid drive train rather than a series one is chosen for several reasons. As shown in Fig.1, the vehicle can be driven by the ICE alone, the EM alone or both engines at the same time utilizing the best performance of each. Unlike series hybrids, parallel hybrids require less number of energy conversion stages and feature less power demands on the electrical system which makes parallel hybrids less expensive and more energy efficient.



Parallel hybrid drivetrain configuration

V. CHOICE OF HYBRID ENERGY STORAGE SYSTEM

HEVs rely on the capability of their ESSs not only to store large amounts of energy but also to discharg according to load demand. A high power, high energy, and high efficiency ESS can be obtained by utilizing a hybrid battery /UC combination. The UC will increase the ESS power handling capability and reserve the amount of regenerative energy dissipated in the friction brakes due to the low power handling capability of the battery. The UC is used during transient pea k power demands and to capture regenerative energy which greatly reduces the voltage variations and stresses across the battery terminals and releases the burden of power converter interfacing the battery.

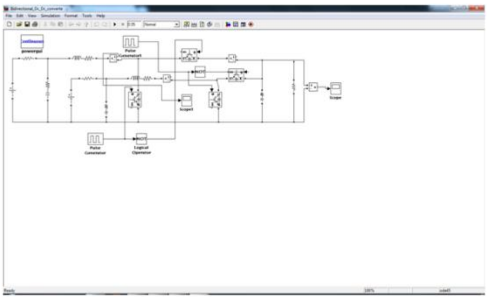
CHOICE OF ELECTRIC AC DRIVE SYSTEM

The AC drive is a classic Permanent Ma gnet Synchronous Motor (PMSM) drive which consists of a PM SM, athree-phase bridge voltage source inverter and a power electronic controller. Voltage source inverters are c ommonly used in HEV applications, where the source delivers a stiff voltage. PMSMs exhibit higher efficiency, higher p ower density and higher torque-to-inertia ratio when comp ared to induction motors. These advantages as well as the fast torque response make PMSMs good candidates for use in HEVs. The main disadvantage is the use of permanent magn ets which are not only expensive but also sensitive to load and temperature.

CHOICE OF POWER ELECTRONICS INTERFACE CONFIGURATION

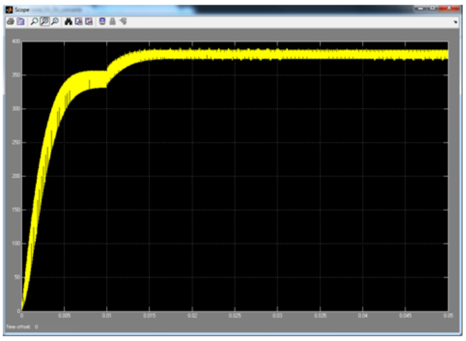
To get full control over the power flowi ng to and from the battery and to limit the fluctuating voltage levels at the UC terminals, it is necessary to utilize a DC/DC PEI between the storage units and the AC drive. The choice of a power converter as simple yet as efficient as possi ble to interface the HESS is discussed in [2]. Accordingly, a parallel dc-linkedmulti-input bidirectional converter is chosen as shown in Fig. 2. The proposed multi-input bidirectional DC/DC converter interfacing the battery/UC HESS and the tr action drive in the HEV consists of two bidirectional half-bridge cells as shown in Fig. 3. Each half-bridge cell consists of an energy storage element (inductor), two IGBT power transistors, and two diodes for bidirectional current flow. IGBTs are chosen since they are suitable for low frequency, high p ower applications such as the full hybrid vehicle considered. An input capacitor interfacing the source acts as a filter limiting the source current ripple and the circulation of high-frequencycomponents through the sources. This filtering is mainly used due to the Equivalent Series Resistance (ESR) of each of the battery and UC pack. Finally, one common output c apacitor is shared between the two cells to minimize the voltag e ripple at the DC bus and the inverter input terminals while t he battery and UC voltages remain at a level lower than that of the dc-link.

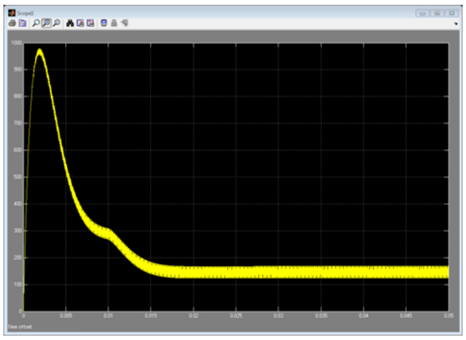
BIDIRECTIONAL DC – DC CONVERTER :



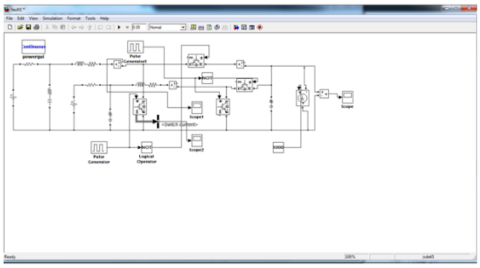
BIDIRECTIONAL DC – DC CONVERTER

OUTPUT OF BIDIRECTIONAL DC-DC CONVERTER:

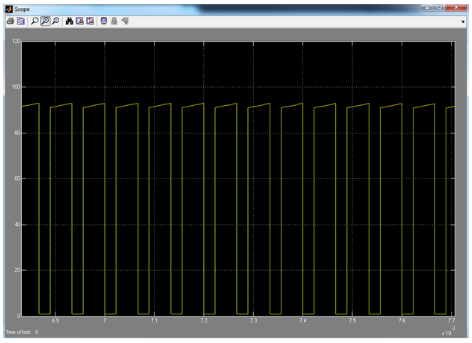


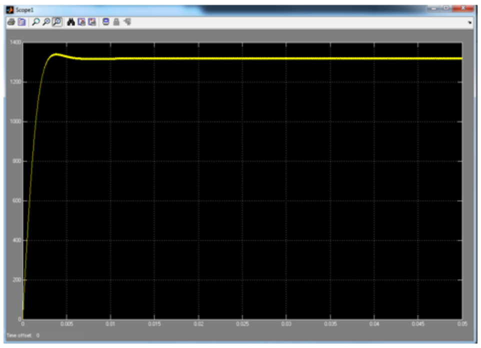


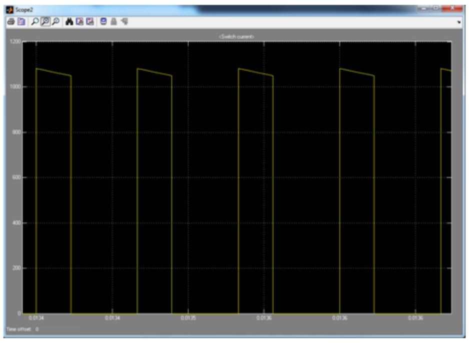
FAULT 1:



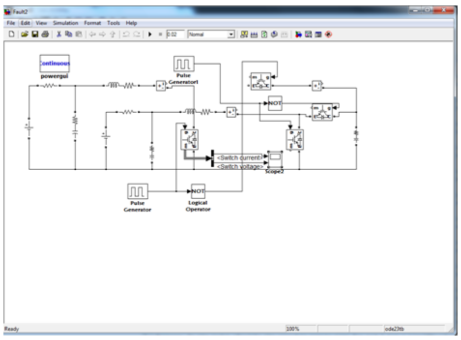
FAULT 1 OUTPUTS:



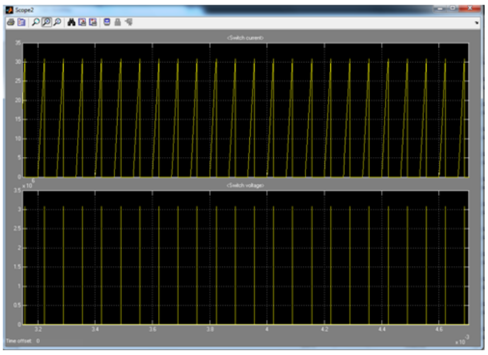




FAULT 2:



FAULT 2 OUTPUT:



VI. CONCLUSION

This paper presents modeling, design and analysis of a half-bridge bidirectional DC/DC converter as a PEI between a HESS and the main DC bus in HEVs. The converter components are sized based on the design requirements of a full HEV. To verify the converter operation, the proposed design is simulated using Matlab/Simulink. Table Vsummarizes the converter simulation results under normal andfaulty conditions for boost and buck operations. The effect of power switching device faults resulting from SC and OC diodes and transistors is analyzed. In summary, fault modes 1, 2, 3, 5, 6, and 7 can damage the power converter; whereas, OC transistor faults do not damage the power converter. When T2 is OC, the energy storage unit is directly to the dc-link; the PEI continues operation but not as a boost converter. When T1 is OC, the energy storage unit is completely disconnected from the dc-link; the converter behaves as if it is shut down. On theother hand, OC diode faults result in high voltage spikes across the converter power switching components which could damage the power device. Whereas, SC diodes and transistors give rise to large bursts of current flowing through the converter components. In conclusion, the parameters measured for control purposes, such as the converter output voltage/current and the inductor voltage and current, can be used as key parameters in detecting and identifying the fault modewheretechniques such as residual redundancy andhigher-order moments are recommended with such types of faults.

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AUTHOR's PROFILE

S. Kartheek received the B.Tech Degree from JNTUA in 2009, Currently pursuing his post graduation (M.tech.) from Gokula Krishna College of Engineering, Sullurpet, SPSR Nellore (Dist), A.P, India.

M.Srinath Received the **B.Tech** degree in Electrical & Electronics engineering from Sri venkateshwara University, Tirupati, Andhra Pradesh, India ,in **2013,** the **M.Tech**. degree in Electrical Engineering from Jawaharlal Nehru Technological University Ananthapur, spsr Nellore,Andhra Pradesh, India, in **2015.** Currently, she is working as a Assistant Professor in the Department of Electrical & Electronics Engineering at Gokula Krishna college of engineering, Sullurpet, SPSR Nellore District, Andhra Pradesh, India. He has one year teaching Experience. His research interest includes power system operation and control,Hvdc Transmission systems and renewable energy sources.

