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Analysis and Design of Improved Isolated Bidirectional Fullbridge DC-DC Converter for Hybrid Electric Vehicle

Divya K. Nair[1]

Asst. Professor, Dept. of EEE, Mar Athanasius College Of Engineering, Kothamangalam, Kerala, India

Abstract: Hybrid electric Vehicles combine the benefits of engine, electric motor and batteries to provide improved fuel economy. A converter is needed in hybrid Electric Vehicle for charging and discharging of the batteries. So a charging and discharging can be combined in one circuit topology known as bidirectional DC-DC converter. Here the output is completely isolated from input, so an isolated bidirectional DC-DC converter is used. In the bidirectional DC-DC converter, there occurs overvoltage and overcurrent stress, which can be reduced by snubber circuits. Various technologies such as RCD, active clamp and flyback snubber for bidirectional DC-DC converter are compared. The bidirectional DC-DC converter with flyback snubber is explained in detail. The simulations are carried out using Simulink/MATLAB 7.6.0 (R2009b) package.

Keywords: Hybrid Electric Vehicles, Bidirectional DC-DC converter, Flyback Snubber, RCD Snubber, Active Clamp Snubber.

I. INTRODUCTION

Electric vehicles, Hybrid Electric Vehicles have been typically proposed to replace conventional vehicles in the near future. The inherent flexibility of Hybrid Electric Vehicles makes them suited for personal transportation and military applications. Hybrid Electric Vehicle combines the benefits of engine and electric motor to provide improved fuel economy. Engine provides most of the vehicle's power and the additional power is provided by the motor when needed such as for accelerating and passing. The electric power for the motor is generated from regenerative braking and from the engine, so Hybrid Electric vehicle don't have to be "plugged" into an electric outlet to recharge.

The bidirectional DC-DC converter is used for both stepping up and stepping down the voltage. Therefore, charging and discharging should be combined in one circuit topology. For the application where the output needs to be completely isolated from the input, isolated converters are employed. For high power applications, full bridge topology is used.

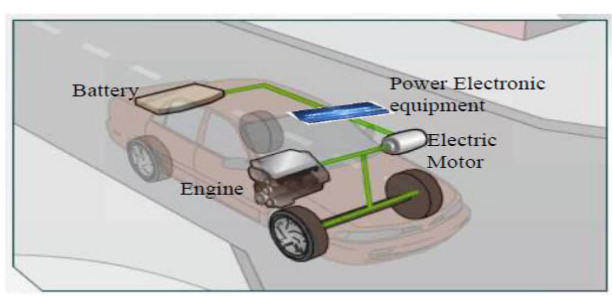

Fig.1. Bidirectional DC-DC converter [1]

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Fig.1 shows an overview of Hybrid Electric Vehicle. The major components are battery, engine, electric motor which can also work as generator and power electronic equipment. Hybrid Electric Vehicle combines the benefits of engine and electric motor to provide improved fuel economy. Engine provides most of the vehicle's power and the additional power is provided by the motor, when needed, such as, for accelerating and passing. The electric power for the motor is generated from the regenerative braking or from the engine, so hybrid electric vehicles don't have to be "plugged" into an electric outlet to recharge [4].

When the vehicle is started, the engine warms up. If necessary, the electric motor acts as a generator, converting energy from the engine into electricity and stores in a battery. The engine powers the vehicle at cruising speeds and if needed, provides power to the battery for future use. During heavy acceleration, both engine and electric motor are used to propel the vehicle. While applying the brake, the kinetic energy of the motor is converted into electricity and this electric energy is stored in the battery. This operation is known as regenerative braking [4] [5].

Batteries in a hybrid electric vehicle are usually required to backup power. Their voltage levels are typically much lower than dc bus voltage. The power electronic equipment used in the hybrid electric vehicle can perform both step-up and step-down operation. Here a bidirectional converter is used for both stepping up and stepping down the voltage and also for charging/discharging of the batteries.

II. CIRCUIT DESCRIPTION

The bidirectional DC-DC converter is used for both stepping up and stepping down the voltage. Therefore, charging and discharging can be combined into one circuit topology. For the application where the output needs to be completely isolated from the input, isolated converters are employed. For high power applications, full bridge topology is used [7].

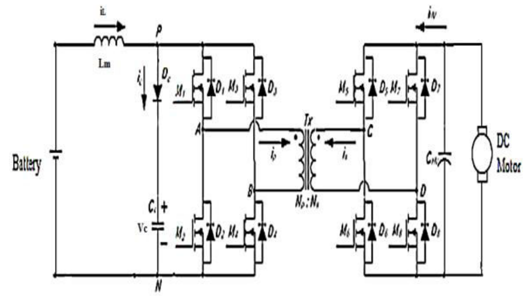

Fig.2 Bidirectional DC-DC converter [7]

In Fig.2, the left hand side is a low voltage side and right hand side is a high voltage side. Low voltage side consists of battery and current fed full bridge and high voltage side consist of voltage fed full bridge. Low voltage side and high voltage side is separated by an isolation transformer with turns ratio, 1:n. Inductor, L_m acts as boost inductor when power flows from the low voltage side to high voltage side, which is described by boost mode of operation. On the other hand, inductor, L_m performs output filtering, when power flows from high voltage to low voltage side, which is described by buck operation. But in the main circuit, there can occur over voltage and over current stress across the MOSFET switches which can be reduced by the snubber circuits [7].

III OPERATION OF THE PROPOSED CONVERTER

A. STEP-UP CONVERSION

In boost mode, switchesM_1–$M_4$are operated like a boost converter, where switch pairs (M_1, M_2) and (M_3, M4) are turned ON to store energy in L_m. At the high-voltage side, the body diodes of switches M_5–M_8 will conduct to transfer

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power to V_{HV}. When switch pair (M_1, M_2) or (M_3, M_4) is switched to (M_1, M_4) or (M_2, M_3), the current difference i_C (= $i_L - i_p$) will charge capacitor C_C , and then, raise $i_p$up to i_L. The clamp branch is mainly used to limit the transient voltage imposed on the current-fed side switches. Moreover, the flyback converter can be controlled to charge the high-voltage-side capacitor to avoid over current. The clamp branch and the flyback snubber are activated during both start-up and regular boost operation modes. A non-phase-shift PWM is used to control the circuit to achieve smooth transition from start-up to regular boost operation mode. Referring to Fig. 3.1, the average power P_C transferred to C_C can be determined as follows:

$$P_C = \frac{1}{2} C_C[(i_L Z_0)^2 + 2 i_L Z_0 V_{C(R)} \qquad (1)$$

where,

$$Z_0 = \sqrt{\frac{L_{eq}}{C_C}} \qquad (2)$$

$$L_{eq} = L_{ll} + L_{lh} \frac{N_p^2}{N_s^2} \qquad (3)$$

where, $V_{C(R)}$ stands for a regulated V_C voltage, which is close to ($V_{HV}(N_P/N_S)$), f_s is the switching frequency, and $L_m >> L_{eq}$. Power P_C will be transferred to the high-side voltage source through the flyback snubber, and the snubber will regulate clamping capacitor voltage V_C to$V_{C(R)}$ within one switching cycle T_s. Note that the flyback snubber does not operate over the interval of inductance current i_p increasing toward i_L. The processed power P_C by the flyback snubber is typically around5% of the full-load power for low-voltage applications. With the flyback snubber, the energy absorbed in C_C will not flow through switches M_1–M_4, which can reduce their current stress dramatically when L_{eq} is significant. Theoretically, it can reduce the current stress from $2i_L$toi_L. The peak voltage $V_{C(P)}$of V_C will impose on M_1–M_4 and it can be determined as follows:

$$V_{C(P)} = i_{L(m)} Z_0 + V_{HV} \frac{N_P}{N_s} \qquad (4)$$

where, $i_{L(M)}$ is the maximum inductor current of i_L, which is related to the maximum load condition. Additionally, for reducing conduction loss, the high-side switchesM_5–$M_8$are operated with synchronous switching. Reliable operation and high efficiency of the proposed converter are verified on a prototype designed for alternative energy applications.

First of all switches M_1-M_4 are turned on, so the primary side of the transformer is short circuited and therefore V_{AB}=0. Inductor, L is charged by the battery. At t_1, M_1& M_4 remain conducting, so V_{AB} is present. Clamping diode, Dc continues to conduct until the current difference drops top zero at t_2. Moreover D_5 and D_8 are conducting to transfer the power. During this interval (i_L-i_P) flows into clamping capacitor. So clamp capacitor voltage, V_C is rising at the interval t_1-t_2 and i_p= i_L condition is reached. During t_2 -t_3, D_c stops conduction and flyback snubber starts to operate. C_c is discharging and the flyback switch is turned on and the energy is stored in flyback snubber as flux. In the interval t_3-t_4 energy stored in the inductor is transferred to high voltage side. Over this interval, flyback snubber will operate independently to regulate $V_{C\ to}$ $V_{C(R)}$. Energy stored in the transformer of the flyback snubber is transferred to the output when flyback switch turns off. At t_4,V_c has been regulated to $V_{C(R)}$ and the snubber remains idle. Over this interval the main power stage is still transferring power from low voltage to high voltage side. It stops at t_5 and completes a half switching cycle operation.

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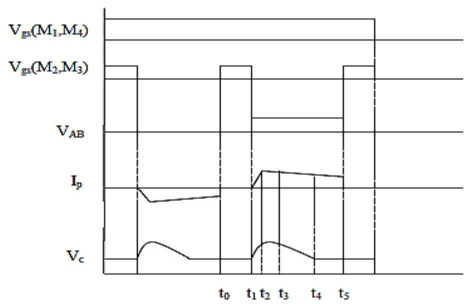

Fig.3 Step-Up Modes of Operation[7]

B.STEP-DOWN CONVERSION

In the analysis, leakage inductance of the transformer at the low-voltage side is reflected to the high-voltage side, as shown in Fig. 2, in which equivalent inductance, L^{*}_{eq} equals the summation of L_{ll} and $L_{lh}\frac{N_p^2}{N_s^2}$. This circuit is known as a phase-shift full-bridge converter. In the step-down conversion, switches M_5–M_8 are operated like a buck converter, in which switch pairs (M_5 , M_8) and (M_6 , M_7) are alternately turned ON to transfer power from V_{HV} to V_{LV}.

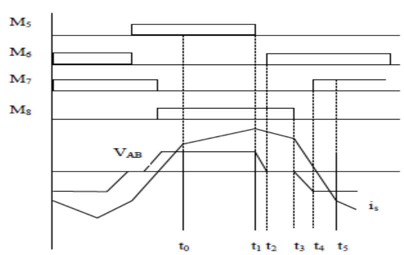

Fig.4 Operation Waveforms of Step Down Conversion[7]

SwitchesM_1–$M_4$are operated with synchronous switching to reduce conduction loss. For alleviating leakage inductance effect on voltage spike, switchesM_5–$M_8$are operated with phase-shift manner. Although, there is no need to absorb the current difference between $i_L$and i_p, capacitor, C_C can help to clamp the voltage ringing due to L_{eq} and parasitic capacitance of M_1–M_4.An isolated bidirectional full bridge DC-DC converter with low-side voltage of 48 V, high side voltage of 360 V, and power rating of 1.5 kW has been designed and implemented. The proposed topology and control is particularly relevant to multiple voltage electrical systems in hybrid electric vehicles and renewable energy generation systems.

During the time period t_0-t_1, switches M_5 and M_8 are on, while switches M_6 and M_7 are in the off state. High side voltage is immediately exerted on the transformer and the whole voltage is exerted on the transformer causing current to rise. With transformer current, i_s increasing linearly towards the load current at t_1, switches, M_1 and M_4 are conducting to transfer the power and the voltage across the transformer terminals on the current fed side changes immediately to reflect the voltage from the voltage fed side.

At t_1, switch M_8 remain conducting, while switch M_5 is turned off. Diode, D_6 starts to conduct the freewheeling leakage current. Transformer current reaches the load current level at t_1 and starts to decrease during the interval t_1-t_2 and voltage V_{AB} starts to decrease. The clamping diode, D_c starts to conduct during this interval.

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At t_2, with diode, D_6 conducting, switch, M_6 can be turned on under ZVS. At t_3, switch M_6 remains conducting, while switch, M_8 is turned off. Diode, D_7 then starts to conduct the freewheeling leakage current.

At t_4, with the diode, D_7 conducting, switch M_7 can be turned on under ZVS. Over this interval, the active switches change to the other pair of diagonal switches and the voltage on the transformer reverse its polarity to balance the flux and to alleviate the transient voltage problem. It stops at t_5 and completes a half switching cycle operation.

A closed loop speed control technique of the proposed battery fed electric vehicle is designed and implemented using PI controller.

III SIMULATIONS AND RESULTS

The simulation of the proposed paper is carried out using MATLAB software. The open and closed loop simulation of buck mode and boost mode is done separately. For open loop simulation, PWM pulses are given as the gating signal. For closed loop simulation, a voltage and current feedback circuit is considered. The isolated bidirectional DC-DC full bridge converter with and without flyback snubber is simulated. The battery fed drive for electric vehicles using isolated bidirectional DC-DC converter with a flyback snubber is also simulated. The simulations are performed with following parameters and the design procedure is explained earlier.

TABLE I SYSTEM PARAMETERS OF HYBRID ELECTRIC VEHICLE [7]

PARAMETERS	VALUES
Input voltage	$V_i = 48V$
Output voltage	$V_o = 360V$
Transformer turns ratio	$N_p: N_s = 1 : 0.133$
Duty cycle	D = 0.8
Switching frequency	$F_s = 25kHz$
Inductor	$L_m = 500\mu H$
Clamping capacitor	$C_c = 1\mu F$
Flyback capacitor	$C_f = 100\mu F$

A. SIMULATION RESULTS OF BOOST OPERATION

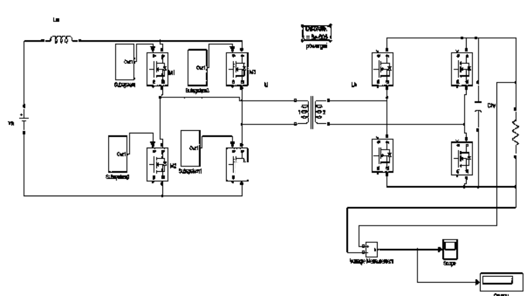

Fig. 5 Simulation circuit of open loop bidirectional full bridge DC-DC converter without flyback snubber- Boost operation

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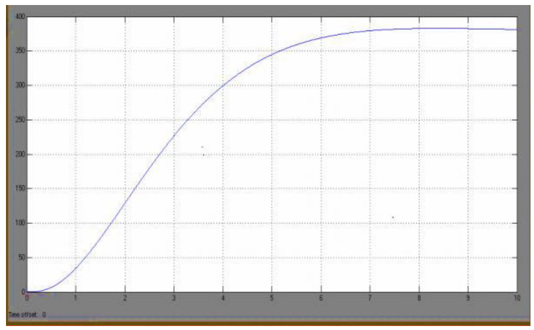
Output voltage [V]



Time [seconds]

Fig.6 Simulation result of open loop bidirectional full bridge DC-DC converter without flyback snubber- Boost operation

We obtain an output voltage of 381.2V for open loop bidirectional full bridge DC-DC converter without flyback snubber.

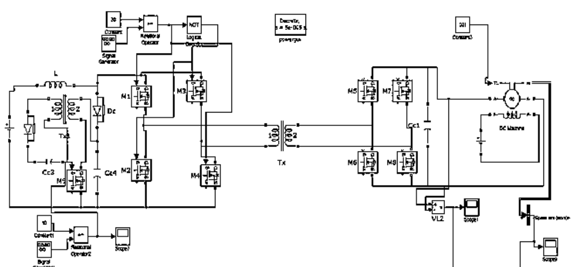
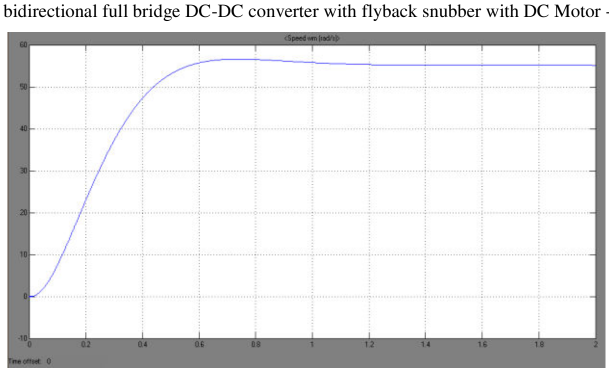


Fig.7 Simulation circuit of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor - Boost open loop operation

Speed (rad/sec)



Time [seconds]

Fig.8 Simulation result of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor - Boost open loop operation (Speed curve)

We obtain a speed of 58.1rad/sec for of bidirectional full bridge DC-DC converter with flyback snubber- Boost open loop operation.

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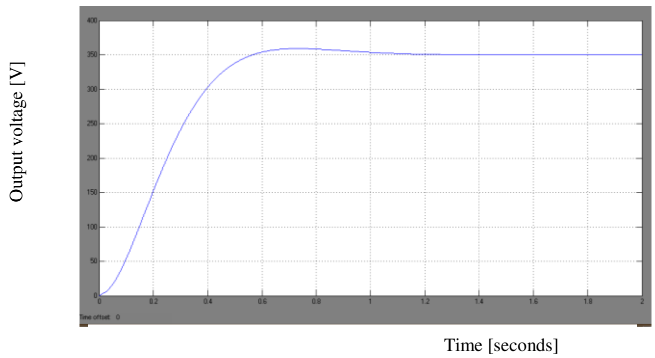

Fig.9 Simulation result of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor - Boost open loop operation with output voltage 350V.

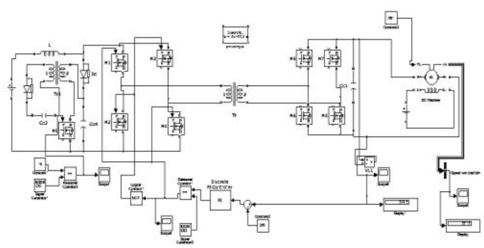

Fig.10 Simulation circuit of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor – Boost closed loop operation

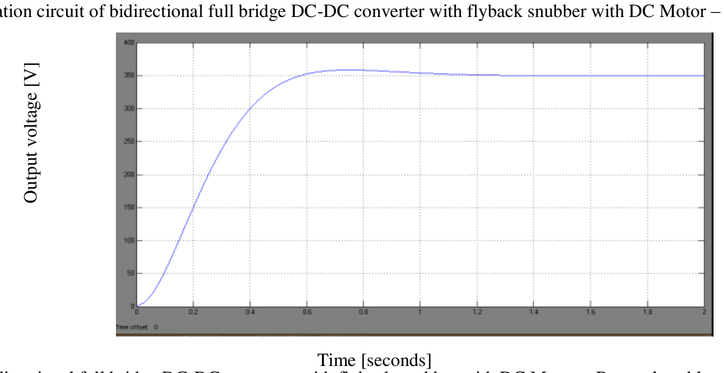

Fig.11 Simulation result of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor – Boost closed loop operation with an output voltage of 350.6V

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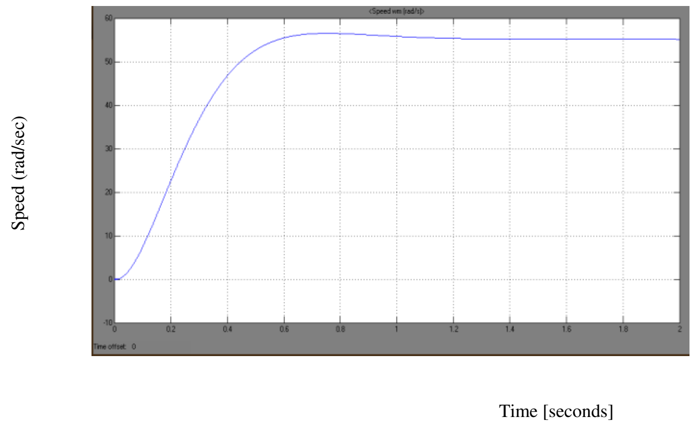

Fig.12 Simulation result of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor – Boost closed loop operation [Speed curve] with a speed of 58.1rad/sec

B. SIMULATION RESULTS OF BUCK OPERATION

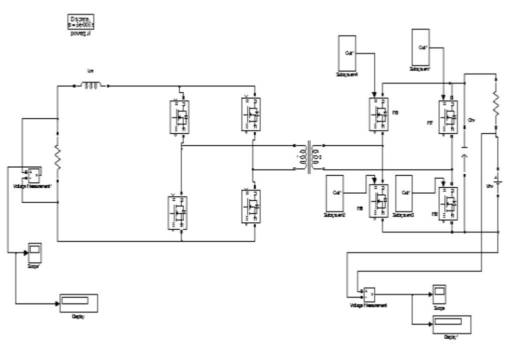

Fig.13 Simulation circuit of open loop bidirectional full bridge DC-DC converter without flyback snubber- Buck operation

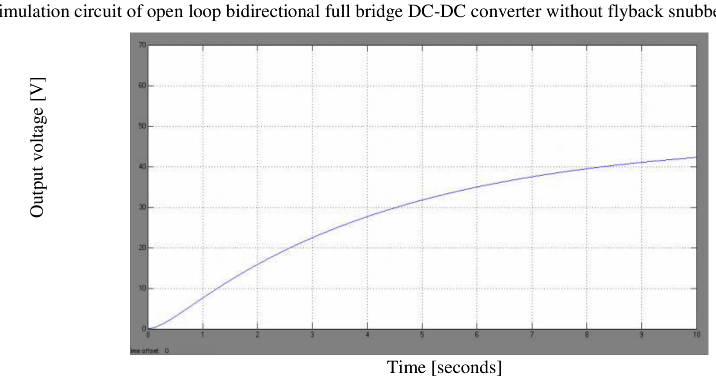

Fig.14 Simulation result of open loop bidirectional full bridge DC-DC converter without flyback snubber- Buck operation

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We obtain an output voltage of 42.86V for open loop bidirectional full bridge DC-DC converter without flyback snubber- Buck operation

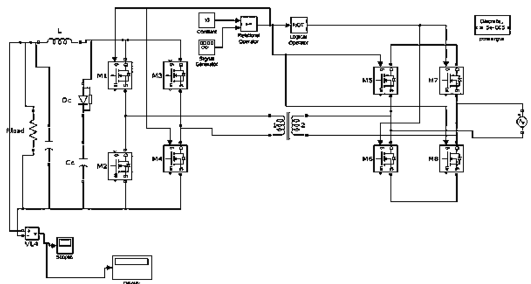

Fig.15 Simulation circuit of bidirectional full bridge DC-DC converter with flyback snubber with DC motor- Buck open loop operation

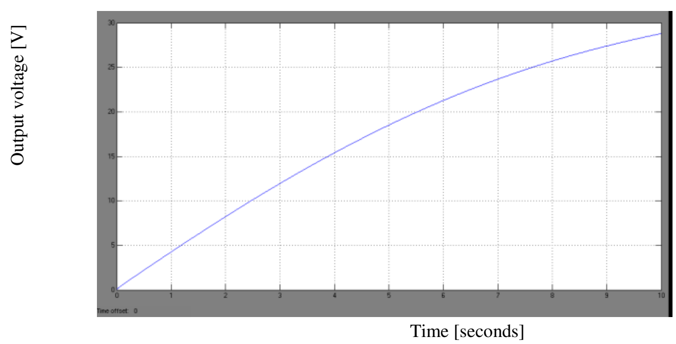

Fig.16 Simulation result of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor - Buck open loop operation with an output voltage of 28.4V.

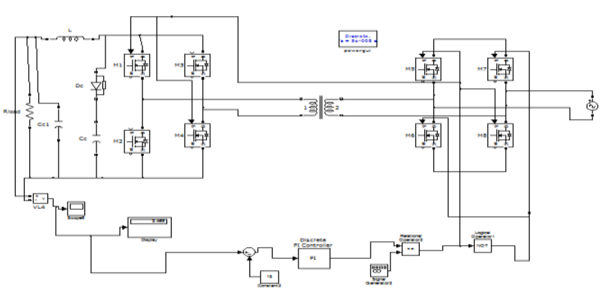

Fig.17 Simulation circuit of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor – Buck closed loop operation

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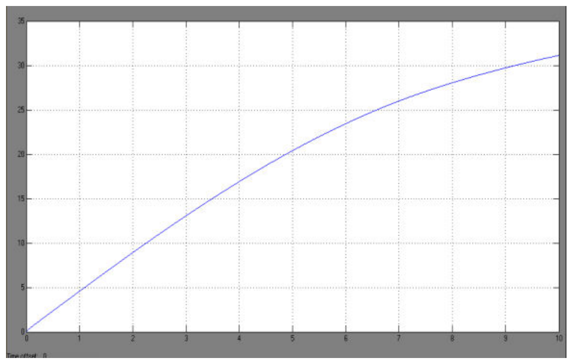

Fig.18 Simulation result of bidirectional full bridge DC-DC converter with flyback snubber with DC Motor – Buck closed loop operation with an ouput voltage of 32.5V

The simulation results of open loop and closed loop control of isolated bidirectional DC-DC converter with and without flyback snubber for various loads are done. DC motor as a load is used for the simulation in hybrid vehicle application.

IV CONCLUSION

Bidirectional dc-dc converters (BDC) have recently received a lot of attention due to the increasing need of systems with the capability of bidirectional energy transfer between two dc buses. Apart from traditional application in dc motor drives, new applications of BDC include energy storage in renewable energy systems, fuel cell energy systems, hybrid electric vehicles (HEV) and uninterruptible power supplies (UPS).

An isolated bidirectional dc-dc converter with a flyback snubber is presented. The flyback snubber can alleviate the voltage spike caused by the current difference between the current fed inductor and leakage inductance of the isolation transformer, and can reduce the current flowing through the active switches. Since the current does not circulate through the full bridge switches, their current stress can be reduced dramatically. The work demonstrates the performance of a hybrid electric vehicle system and it shows satisfactory performance at different driving condition. The proposed control technique with PI controller find suitable for this electric drive.

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