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A BIDIRECTIONAL VERSATILE BUCK–BOOST CONVERTER DRIVER FOR ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

The level of exhaust gases is rising with increasing usage of internal combustion engine vehicles. In order to reduce carbon emission, researchers and industry head up for improving electric vehicle technologies in all over the word. This paper deals with design and simulation of a bi-directional power converter of electric vehicle. The power electronics block is comprised by batteries, bi-directional dc-dc converter and BLDC machine. The initial state of battery charge is set around 90% where the discharge current is 44.5 A during motor mode. The nominal voltage of battery stack is 350 V and maximum capacity is 100 Ah. The operating mode of power converter is determined according to the torque values of BLDC machine which is operated in motor and generator modes. The charge and discharge conditions of batteries have been controlled regarding to operating modes of dc machine. The proposed converter and controller are designed to meet charge control and motor drive requirements of an all-electric vehicle.

I. INTRODUCTION

Transportation sector occupies a fundamental place in the world. Fossil fuels used in conventional vehicles technology emit greenhouse gases such as carbon dioxide, carbon monoxide and methane. The excessive consumption of these gases causes air pollution, climate change and global warming. In order to reduce these effects, there is a tendency to electric vehicle (EV) technology. The EV has much lower fuel cost according to fossil fueled car since they are mainly composed of battery system, power electronic circuits and electric machine. The battery system in an EV is the most crucial component in charge control time and determining distance [1,2]. The electric machines of an EV are operated in both motor and generator modes due to regenerative breaking feature that enables electric machine to be operated in generator mode which is impossible in conventional internal combustion engine (ICE) vehicles. Therefore, electric machine charges the battery by operating in generator mode during the regenerative braking and it ensures recharging the batteries [3,4]. EV is classified into two types as hybrid EVs (HEVs) and all-electric vehicles. The HEV technology is used in conjunction conventional vehicle technology. The main system in HEV technology includes fuel tank and ICE such as diesel or gasoline engine, and auxiliary system which is comprised by electric machine, power electronic circuits and battery. HEVs are classified as parallel and series hybrid vehicles [5] that the parallel HEV consists ICE and electrical machine together as shown in Fig.1. As the parallel electric vehicles operate at electric mode during the acceleration of electric machine, the motor operation is supplied from battery. The designed EV motor driver is comprised by four sections such as battery, bi-directional dc-dc converter, FLC and dc machine as shown In this study, the starting voltage of battery is set to 378 V while the operating voltage of dc machine used in traction system is 500 V dc. The battery voltage is increased up to 500 V with bi-directional dc-dc converter in generator mode. The battery is discharged when dc machine is started acceleration. The motor mode simulation with various torque values are performed to observe battery parameters such as state of charge (SoC), current, voltage and voltage of the dc machine. The voltage of the dc machine is decreased to 500 V with bidirectional dc-dc converter which is controlled with FLC. The battery is charged during the generator mode operation of dc machine. The FLC determines duty cycle of S1 and S2 to ensure charge and discharge of battery. The dc machine is comprised by brushes, armature core and windings, commutator, field core and windings. Armature circuit is comprised by series structure with inductor, resistance and counter-electromotive source. Similarly, battery parameters such as SoC, current, voltage and voltage of the dc machine are observed in the generator mode simulation regarding to various torque values applied to dc machine.

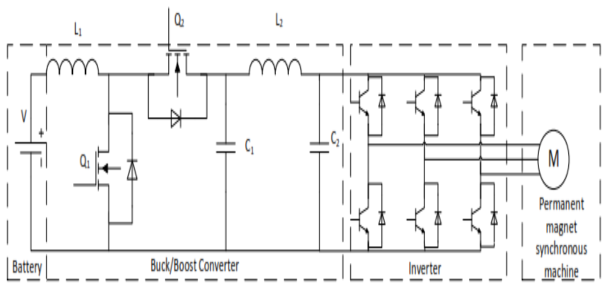

Fig.1 Proposed circuit configuration

The electrical energy is converted to mechanical energy or vice versa by dc machine that operates regarding to electromechanical energy conversion theory [7]. If a conductor is moved within the magnetic field, the voltage is induced on it which is known as generator operating mode. If alternating current passes through the conductor, magnetic field is created around it which explains the motor mode operation. When the dc machine is started acceleration, the resultant positive torque is achieved. On the other hand, negative torque is generated at the dc machine when it is operated in generator mode

FLC is comprised by fuzzification, rule base, interface mechanism, defuzzification. Fuzzification is used to convert digital signals received through the system into linguistic variable. Rule base is comprised by the conditions to set for controlling the system at desired location. Interface mechanism makes inferences according to the rules of system by establishing a relationship between inputs. Defuzzification is used to convert linguistic variable received through the system into digital signals

The European new vehicle CO2 regulation (with a mandatory target value of 95 grams of CO2 per kilometer by 2021 for passenger cars) is currently in the process of being extended to 2025. In this context, one of the key questions is at what point a significant uptake of the electric vehicle market is to be expected. In order to help inform this debate about how electric vehicle technology could fit in a lower-carbon 2020–2030 new vehicle fleet in Europe, this paper focuses on collecting, analyzing, and aggregating the available research literature on the underlying technology costs and carbon emissions. In terms of technologies, this paper concentrates on the three electric propulsion systems: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles (HFCEVs). The collected cost data is used to estimate the technology cost for automotive lithium-ion (Li-ion) batteries and fuel cells. The cost of battery packs for BEVs declined to an estimated €250 per kWh for industry leaders in 2015. Further cost reductions down to as low as €130–€180 per kWh are anticipated in the 2020–25 time frame. The costs of fuel cell systems are also expected to decrease considerably, but cost estimates are highly uncertain. Furthermore, the application of fuel cells and batteries in HFCEVs, BEVs, and PHEVs is approximated using a bottom-up cost approach. Overall, the different power train costs largely depend on battery and fuel cell costs.

This paper concludes that the costs of all power trains will decrease significantly between 2015 and 2030 (Figure S 1). As shown, power trains for PHEVs will achieve about a 50% cost reduction, compared with approximate cost reductions of 60% for BEVs and 70% for HFCEVs. Costs for hydrogen and electricity chargers are estimated separately. Greenhouse gas (GHG) emissions and energy demand for electric and conventional vehicles are presented on a well-to-wheel (WTW) basis, capturing all direct and indirect emissions of fuel and electricity production and vehicle operation. The results are based on former analyses, and are updated and refined with real-world fuel consumption levels. Real-world fuel consumption is commonly about 20%–40% higher than official type approval measurements. Finally, WTW estimates for electric and conventional vehicles are put in the context of the 2021 CO2 standard for European passenger vehicles. It is found that carbon emissions of BEVs using European grid-mix electricity are about half of average European vehicle emissions, whereas HFCEVs and PHEVs have a lower emissions reduction potential. In the 2020 context, electric vehicle WTW emissions are expected to continue offering greater carbon benefits due to more efficient power trains and increasing low-carbon electric power. A lower-carbon grid and higher power train efficiency by 2020 could cut average electric vehicle emissions by one-third again. However, the expected cost reductions and potential CO2 emission cuts will not be achieved without targeted policy intervention. More stringent CO2 standards, and fiscal and non-fiscal incentives for electric vehicles, can help the electric vehicle market to grow and costs to fall. Also, efforts need to be combined with activities to decarbonize the grid, or emission reductions will not be as great as they could be. Although the analysis is focused on the European context, similar dynamics with electric vehicle technology, policy, and market development are prevalent across major markets in North America and Asia.

II. BATTERY STORAGE SYSTEM

A battery is a device consisting of one or more electrochemical cells with external connections for powering electrical devices such as flashlights, mobile phones, and electric cars. When a battery is supplying electric power, its positive terminal is the cathode and its negative terminal is the anode.[2] The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal. When a battery is connected to an external electric load, a redox reaction converts high-energy reactants to lower-energy products, and the free-energy difference is delivered to the external circuit as electrical energy. Historically the term "battery" specifically referred to a device composed of multiple cells, however the usage has evolved to include devices composed of a single cell.

Primary (single-use or "disposable") batteries are used once and discarded, as the electrode materials are irreversibly changed during discharge; a common example is the alkaline battery used for flashlights and a multitude of portable electronic devices. Secondary (rechargeable) batteries can be discharged and recharged multiple times using an applied electric current; the original composition of the electrodes can be restored by reverse current. Examples include the lead-acid batteries used in vehicles and lithium-ion batteries used for portable electronics such as laptops and mobile phones.

Batteries come in many shapes and sizes, from miniature cells used to power hearing aids and wristwatches to small, thin cells used in smart phones, to large lead acid batteries or lithium-ion batteries in vehicles, and at the largest extreme, huge battery banks the size of rooms that provide standby or emergency power for telephone exchanges and computer data centers.

Batteries have much lower specific energy (energy per unit mass) than common fuels such as gasoline. In automobiles, this is somewhat offset by the higher efficiency of electric motors in converting chemical energy to mechanical work, compared to combustion engines.

The usage of "battery" to describe a group of electrical devices dates to Benjamin Franklin, who in 1748 described multiple Leyden jars by analogy to a battery of cannon (Benjamin Franklin borrowed the term "battery" from the military, which refers to weapons functioning together).

Italian physicist Alessandro Volta built and described the first electrochemical battery, the voltaic pile, in 1800.This was a stack of copper and zinc plates, separated by brine-soaked paper disks, which could produce a steady current for a considerable length of time. Volta did not understand that the voltage was due to chemical reactions. He thought that his cells were an inexhaustible source of energy, and that the associated corrosion effects at the electrodes were a mere nuisance, rather than an unavoidable consequence of their operation, as Michael Faraday showed in 1834.

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III. PROPOSED DC-DC CONVERTER

Buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is equivalent to a fly back converter using a single inductor instead of a transformer. Two different topologies are called buck–boost converter. Both of them can produce a range of output voltages, ranging from much larger (in absolute magnitude) than the input voltage, down to almost zero.

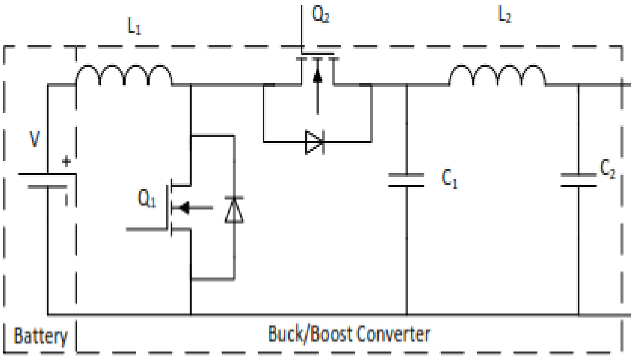

Fig. 2 Proposed converter

The output voltage is of the opposite polarity than the input. This is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. However, this drawback is of no consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) because the supply and diode polarity can simply be reversed. When they can be reversed, the switch can be on either the ground side or the supply side.

A buck (step-down) converter combined with a boost (step-up) converter

The output voltage is typically of the same polarity of the input, and can be lower or higher than the input. Such a non-inverting buck-boost converter may use a single inductor which is used for both the buck inductor mode and the boost inductor mode, using switches instead of diodes,[2][3] sometimes called a "four-switch buck-boost converter", it may use multiple inductors but only a single switch as in the SEPIC and Ćuk topologies.

A. Buck Boost converter-principle of operation-applications

A Buck converter is a switch mode DC to DC converter in which the output voltage can be transformed to a level less than or greater than the input voltage. The magnitude of output voltage depends on the duty cycle of the switch.It is also called as step up/step down converter. The name step up/step down converter comes from the fact that analogous to step up/step down transformer the input voltage can be stepped up/down to a level greater than/less than the input voltage. By law of conservation of energy the input power has to be equal to output power (assuming no losses in the circuit).

Input power (P_{in}) = output power (P_{out})

In step up mode $V_{in} < V_{out}$ in a Buck Boost converter, it follows then that the output current will be less than the input current. Therefore for a Buck Boost converter in step up mode

$$V_{in} < V_{out} \text{ and } I_{in} > I_{out}$$

In step down mode $V_{in} > V_{out}$ in a Buck Boost converter, it follows then that the output current will be greater than the input current. Therefore for a Buck boost converter in step down mode

$$V_{in} > V_{out} \text{ and } I_{in} < I_{out}$$

Principle of operation of Buck converter

The main working principle of Buck Boost converter is that the inductor in the input circuit resists sudden variations in input current. When switch is ON the inductor stores energy from the input in the form of magnetic energy and discharges it when switch is closed. The capacitor in the output circuit is assumed large enough that the time constant of RC circuit in the output stage is high. The large time constant compared to switching period ensures that in steady state a constant output voltage $V_o(t) = V_o(\text{constant})$ exists across load terminals.

Circuit diagram of Buck Boost converter

The circuit diagram of Buck Boost converter is shown in the figure below

Modes of operation of Buck Boost converter

The Buck Boost converter can be operated in two modes

a) Continuous conduction mode in which the current through inductor never goes to zero i.e. inductor partially discharges before the start of the switching cycle.

b) Discontinuous conduction mode in which the current through inductor goes to zero i.e. inductor is completely discharged at the end of switching cycle.

Circuit analysis of Buck converter

Assume in the entire analysis that the current swing (maximum to minimum value) through inductor and voltage swing through capacitor is very less so that they vary in a linear fashion. This is to ease the analysis and the results we will get through this analysis are quite accurate compared to real values.

B. Continuous conduction mode

Case-1: When switch S is ON

When switch in ON for a time t_{on}, the diode will be open circuited since it does not allow currents in reverse direction from input to output. Hence the Buck Boost converter can be redrawn as follows

During this state the inductor charges and the inductor current increases. The current through the inductor is given as

$$I_L = (1/L) * \int V * dt$$

Assume that prior to the opening of switch the inductor current is $I'_{L,off}$. Since the input voltage is constant

$$I_{L,on} = (1/L) * \int V_{in} * dt + I'_{L,on}$$

Assume the switch is open for ton seconds which is given by $D*T_s$ where D is duty cycle and T_s is switching time period. The current through the inductor at the end of switch on state is given as

$$I_{L,on} = (1/L) * V_{in} * D * T_s + I'_{L,on} \text{ (equation 1)}$$

Hence $\Delta I_{L,on} = (1/L)*V_{in}*D*T_s$.

Case 2: When switch is off

When switch in OFF the diode will be forward biased as it allows current from output to input (p to n terminal) and the Buck Boost converter circuit can be redrawn as follows

The inductor now discharges through the diode and RC combination. Assume that prior to the closing of switch the inductor current is $I''_{L,\,off}$. The current through the inductor is given as

$$I'''_{L,off} = -(1/L) * \int V_{out} * dt + I''_{L,off}$$

Note the negative sign at the front end of equation signifies that the inductor is discharging. Assume the switch is open for t_{off} seconds which is given by (1-D)*T_s where D is duty cycle and T_s is switching time period. The current through the inductor at the end of switch off state is given as

$$I'''_{L,\,off} = -(1/L) * V_{out} * (1-D) * T_s + I''_{L,\,off} \text{ (equation 2)}$$

In steady state condition as the current through the inductor does not change abruptly, the current at the end of switch on state and the current at the end of switch off state should be equal. Also the currents at the start of switch off state should be equal to current at the end of switch on state. Hence

$$I'''_{L,\,off} = I_{L,\,on} \text{ also } I'_{L,\,off} = I''_{L,\,off}$$

Using the equations 1 and 2 we get

$(1/L) * V_{in} * D * T_s = (1/L) * V_{out} * (1-D) * T_s$

$V_{in} * D = V_{out} * (1-D)$

$V_{out}/V_{in} = D/(1-D)$

Since D < 1, V_{out} can be greater than or less than V_{in}.For D>0.5 the Buck boost converter acts as boost converter with $V_{out} > V_{in}$.For D<0.5 the Buck boost converter acts as buck converter with $V_{out} > V_{in}$.

Assuming no losses in the circuit and applying the law of conservation of energy

$$V_{out} * I_{out} = V_{in} * I_{in}$$

This implies $I_{out}/I_{in} = (1-D)/D$, Thus $I_{out} > I_{in}$ for D<0.5 and $I_{out} < I_{in}$ for D<0.5 . As the duty cycle increases the output voltage increases and output current decreases.

C) Discontinuous conduction mode

As mentioned before the converter when operated in discontinuous mode the inductor drains its stored energy completely before completion of switching cycle. The current and voltage wave forms of Buck Boost converter in discontinuous mode is shown in the figure below

The inductor in discontinuous mode drains all the current which it piled up in charging interval of same switching cycle. The current through the inductor is given as

$$I_L = (1/L) \int V_L * dt$$

= (1/L)*area under the curve of voltage v/s time. Hence from the wave forms shown in the figure

$V_{out} * \delta * T_s = V_{in} * D * T_s$

$$V_{out}/V_{in} = D/\delta$$

and the ratio of output to input current from law of conservation of energy is $I_{out}/I_{in} = \delta/D$.

Applications of Buck boost converter

- It is used in the self regulating power supplies.
- It has consumer electronics.
- It is used in the Battery power systems.
- Adaptive control applications.
- Power amplifier applications.
- Cheap to make.
- Little heat whilst working.
- Low power consumption.
- Can utilize very high frequencies (40-100 Khz is not uncommon.)
- Very energy-efficient when used to convert voltages or to dim light bulbs.
- High power handling capability
- Efficiency up to 90%

Modulation technique used to encode a message into a pulsing signal. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors. In addition, PWM is one of the two principal algorithms used in photovoltaic solar battery chargers, the other being MPPT.

The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load. The PWM switching frequency has to be much higher than what would affect the load (the device that uses the power), which is to say that the resultant waveform perceived by the load must be as smooth as possible. Typically switching has to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

The term duty cycle describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on.

The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM also works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle.

PWM has also been used in certain communication systems where its duty cycle has been used to convey information over a communications channel.

An example of PWM in an idealized inductor driven by a voltage source: the voltage source (blue) is modulated as a series of pulses that results in a sine-like current/flux (red) in the inductor. The blue rectangular pulses nonetheless result in a smoother and smoother red sine wave as the switching frequency increases. Note that the red waveform is the (definite) integral of the blue waveform.

Principle

Pulse-width modulation uses a rectangular pulse wave whose pulse width is modulated resulting in the variation of the average value of the waveform. If we consider a pulse waveform $f(t)$, with period T, low value y_{min}, a high value y_{max} and a duty cycle D (see figure 1), the average value of the waveform is given by:

$$\bar{y} = \frac{1}{T}\int_0^T f(t)\,dt.$$

As $f(t)$ is a pulse wave, its value is y_{max} for $0 < t < D \cdot T$ and y_{min} for $D \cdot T < t < T$. The above expression then becomes:

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$$\bar{y} = \frac{1}{T}\left(\int_0^{DT} y_{max}\,dt + \int_{DT}^{T} y_{min}\,dt\right) = \frac{D \cdot T \cdot y_{max} + T\,(1-D)\,y_{min}}{T} = D \cdot y_{max} + (1-D)\,y_{min}.$$

This latter expression can be fairly simplified in many cases where $y_{min} = 0$ as $\bar{y} = D \cdot y_{max}$. From this, it is obvious that the average value of the signal ($\bar{y}$) is directly dependent on the duty cycle D.

The simplest way to generate a PWM signal is the interceptive method, which requires only a saw tooth or a triangle waveform (easily generated using a simple oscillator) and a comparator. When the value of the reference signal (the red sine wave in figure 2) is more than the modulation waveform (blue), the PWM signal (magenta) is in the high state, otherwise it is in the low state.

IV. SIMULATION RESULTS

The results obtained make it possible to determine the limit (limit) values of currents and voltages in the power circuit. In this way, design restrictions are set, such as the topology type, the control frequency, and so on. On the other hand, the presented model may be reduced using some of the known model reduction techniques. In this way, numerical experiments with large simulation times (of the order of minutes) are possible. This is important when complex objects with different time constants are modeled: the electronics, the electric motor and the mechanical part of the vehicle. In further researches the proposed model could be significant contribution for examination of different driving cycles such as urban and suburban. The determination of the optimal control of energy flows could be considerably simple with the aid of these researches. Thus, this study could assist with the evaluation of the efficiency of the electric vehicle.

A. Mat lab Proposed converter

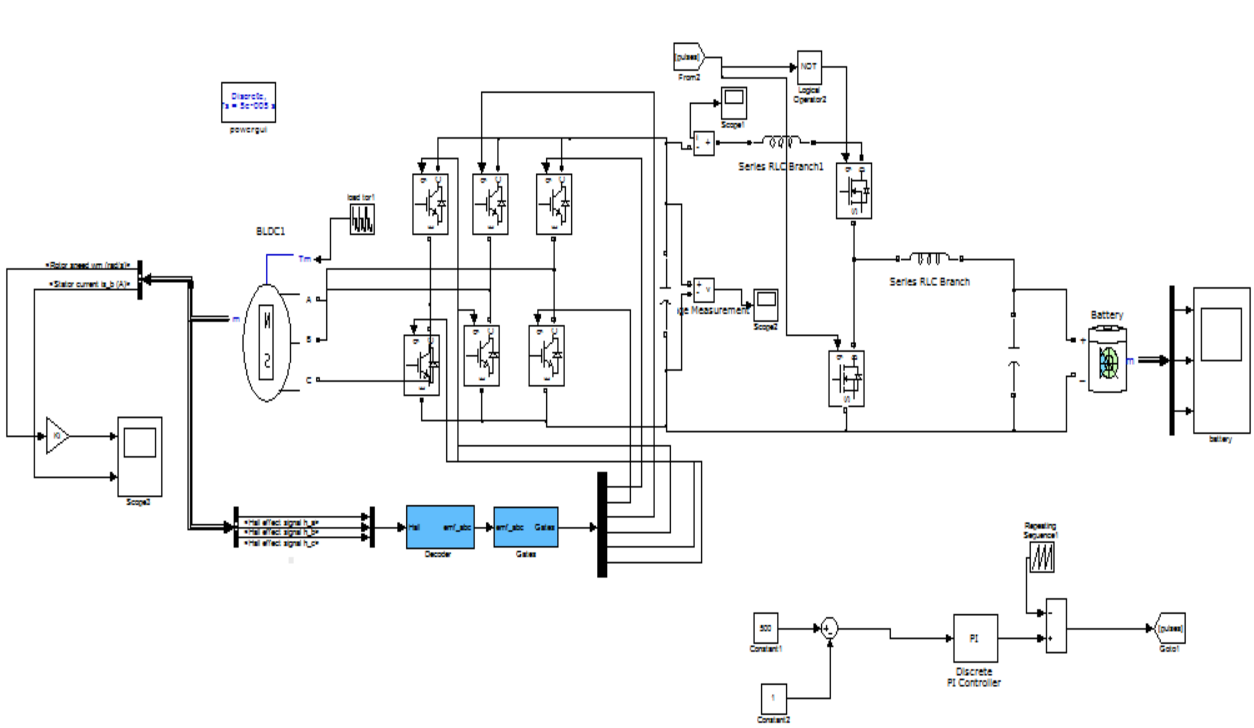

Fig. 3 Simulation model

Simulation outputs

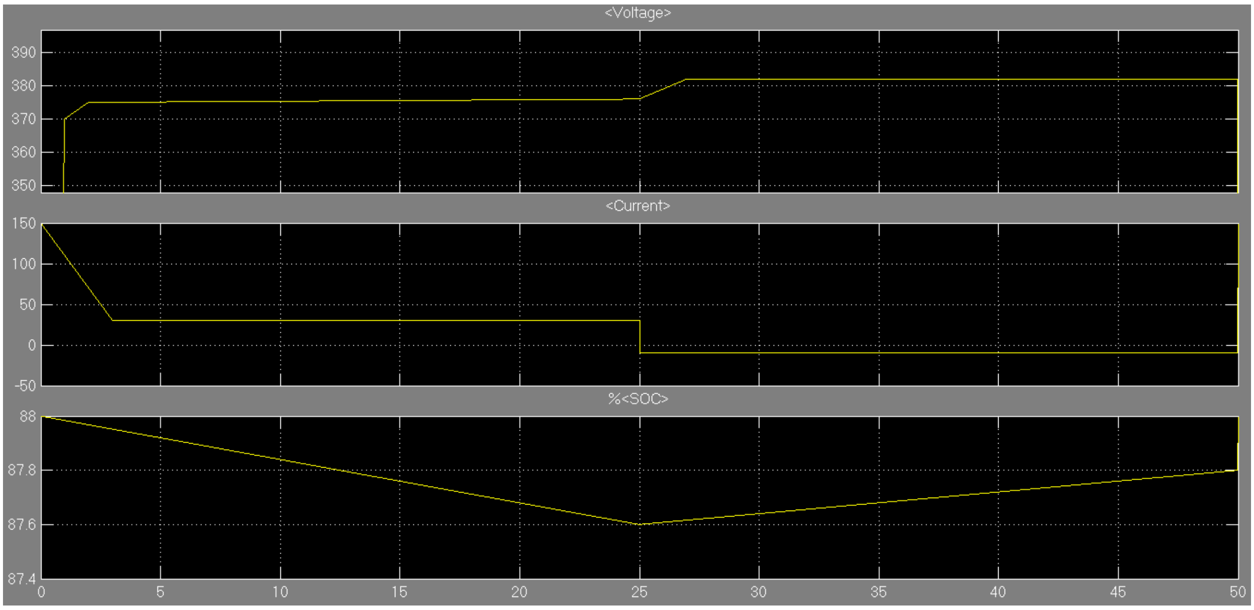

Fig.4 Voltage, current and Soc of the battery

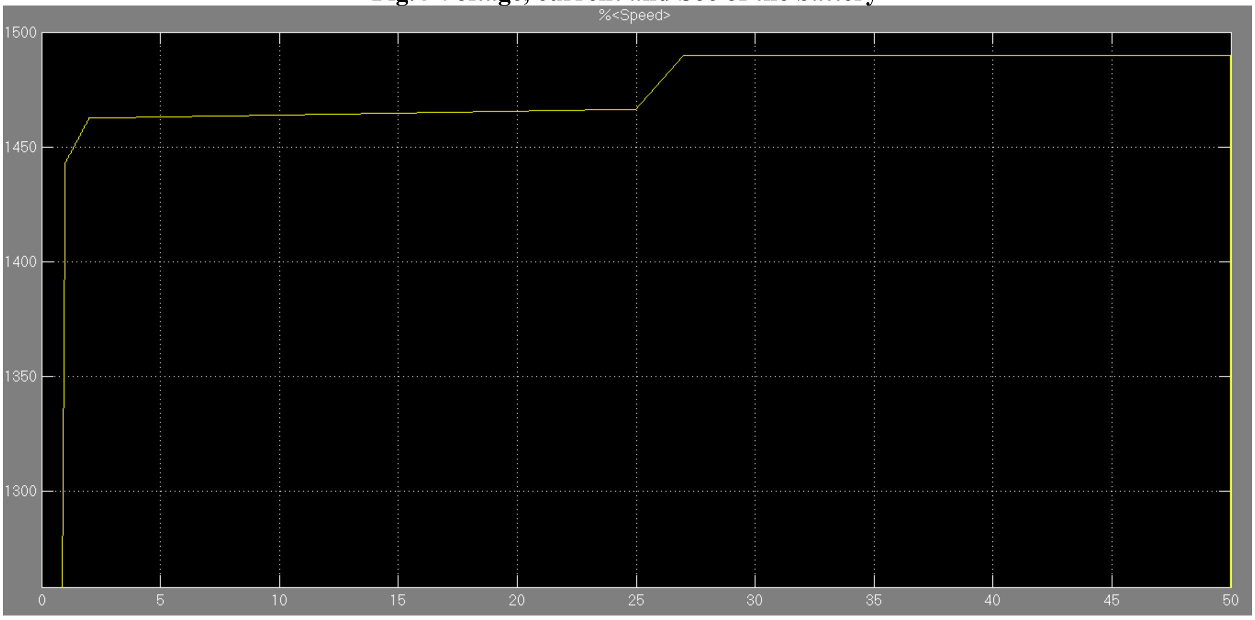

Fig. 5 Speed of proposed BLDC

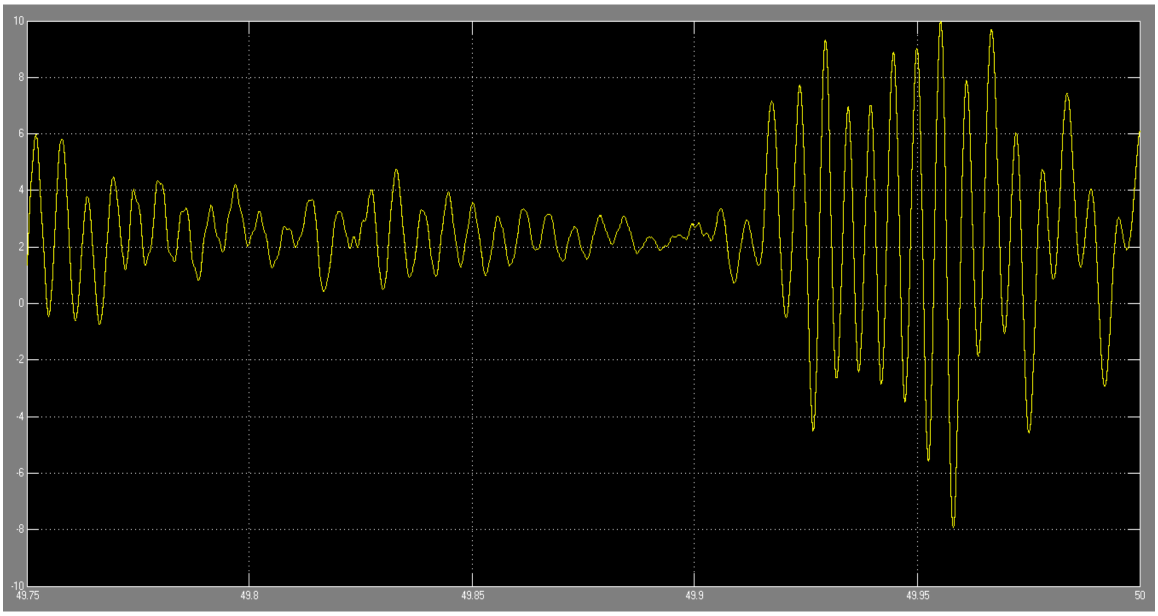

Fig.6 Current through the inductor L2

The model of a DC motor is realized with equivalent damping resistance. In Fig. 5.4 shows the output current of the DC-DC converter (the current through the inductor L2). In both figures, the X axis indicates the simulation time in seconds.

V. CONCLUSION

This project presents design and control bi-directional dc-dc converter for all-electric vehicle. When the battery is discharged, the dc machine is operated in motor mode and bi-directional dc-dc converter is operated in boost mode. Variable positive torque values are applied to the BLDC machine and condition of the battery is observed. According to simulation result, the battery SoC is reduced from %88 to %87.337 and voltage of the dc machine is constant at 500 V. When the battery is charged, the machine is operated generator mode and bi-directional dc-dc converter is operated in buck mode. Variable negative torque values are applied to the BLDC machine and effect on the battery is observed. According to simulation result, the battery SoC is increased from %87.337 to %87.445. In all-electric vehicle, regenerative breaking is occurred in this state. Charge and discharge states of the battery are the most essential for distance to determining.

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