

## MODELING AND CONTROL OF DC-DC BIDIRECTIONAL CONVERTER FOR ELECTRIC VEHICLE (EV) DRIVE SYSTEM

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Accepted: 20<sup>th</sup> November, 2023

Review: 29<sup>th</sup> November, 2023

Approved: 14<sup>th</sup> December, 2023

### ABSTRACT

*In order to reduce carbon emission from the usage of internal combustion engine vehicles, researchers and Engineers has put efforts in recent time in electric vehicle technologies. This paper presents modelling and control of electric vehicle drive system using a bi-directional DC-DC converter. The drive system is comprised of Lithium-ion batteries, bi-directional half bridge Buck boost DC-DC converter, Fuzzy logic controller and DC machine. The provision for energy regeneration is achieved by using halfbridge non isolated DC-DC converter. The initial State of Charge (SOC) is set at 85% where the discharge current is 19.5A during motor mode. The nominal voltage of battery stack is set at 380V with maximum capacity of 100Ah. The rated power of DC machine is set to 250HP with 500V armature voltage and 300V field voltage. The operating mode of power converter is determined according to the torque values of DC machine which is operated in motor and generator modes. The bi-directional DC-DC converter is controlled with Fuzzy logic controller in both modes. Fuzzy logic controller has been implemented for charge control. The system model has been simulated in the MATLAB/SIMULINK. The various waveforms corresponding to the motor speed, armature current, SOC, battery voltage and the battery current during simulation has been plotted and evaluated. From Simulation result verification, its shows that the proposed converter with Fuzzy logic controller is effective and efficient in charging system for Electric Vehicle.*

**Keywords:** Bi-directional DC-DC converter, DC machine, Fuzzy logic controller (FLC), PWM

### I. INTRODUCTION

The importance of developing vehicles using alternative energy sources has raised interest in bidirectional Direct Current to Direct Current (DC-DC) converter. This eventually results in increasing the overall efficiency of vehicle. (Mane and A.M Jain 2015). 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 need to use Electric Vehicle (EV) which is environmentally friendly. The EV has much lower cost compared 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. The electric

machines of an EV are operated in both motor and generator modes due to regenerative braking 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. EV are classified into two types as Hybrid Electric Vehicles (HEVs) and all-electric vehicles. Also, Pure Battery Electric Vehicles (BEVs) are also referred to as Battery-only Electric Vehicles (BOEVs). BEVs have no engine and are propelled by electricity that comes from one or several onboard high-energy batteries. Modern models use a regenerative braking system to save energy. Examples include the Renault Zoe and the Nissan Leaf. The Zoe has a 22 kWh Li-ion battery, and an energy consumption of 14.6 kWh per 100 km. The 2015 Leaf comes with a 24-kWh

battery, Plug-in Hybrid Electric Vehicles (PHEVs) allow electric driving on batteries (in charge-depleting mode), but also conventional combustion fueled driving (in charge-sustaining mode). PHEVs and BEVs use similar batteries, with Li-ion being the most common chemistry. The battery system is the key technology of electric vehicles and defines their range and performance characteristics. (M. K. Rani, V. L. Lakshmi, 2022). Yadlapalli et al., (2022) presented a work on the technological advancements of the electric vehicles (EVs) all over the world. Their first emphasis was on the various types of the EVs along with the energy management strategies (EMSs). The EVs were equipped with different energy storage elements such as lithium-ion batteries, super capacitors (SCs) and fuel cells (FCs). Hence, they optimized the power split between the various energy storage systems (ESSs) under the complex driving conditions. The second imperative aspect was the utilization of the energy efficient wide bandgap (WBG) semiconductor technology. The WBG materials presented the superior properties like wide bandgap, high saturated drift velocity and high critical breakdown field. In this paper present modeling and control of Electric Vehicle (EV) drive system using DC-DC bidirectional buck boost converter with fuzzy logic controller.

## II. METHODOLOGY

Feedback control technique is adopted for regulation of electric vehicle (EV) battery charge and voltage using bidirectional dc-dc converter with fuzzy logic controller which evaluate voltage error. The electric vehicle drive system comprises of subsystems such as Dc machine (PMDCM), Controller, Bidirectional converter and Lithium ion battery . the system model is developed using MATLAB/SIMULINK software.

### (A) Modelling of PMDCM

The DC motor is mathematically modelled by taking into consideration the torque and rotor angle relationship. According to the Kirchhoff's voltage law on armature circuit. The armature voltage of the DC motor is described as:

$$V_a = L_a \left( \frac{di_a}{dt} \right) + R_a i_a + E_g \quad (1)$$

The back emf voltage ( $E_g$ ) is proportional to the angular speed ( $\omega$ ) of the rotor in the motor, expressed as

$$E_g = K_v \omega i_f = K_b \omega \quad (2)$$

The relation between steady state motor torque T, armature current I and torque constant K is given as,

$$\text{Developed Torque is also expressed as: } T_m = K_t i_f i_a = K_t i_a \quad (3)$$

For normal operation, Newton's laws, the mechanical equation can be described by the following equation,

$$T_m = J \left( \frac{d\omega}{dt} \right) + B\omega + T_L \quad (4)$$

The transfer function of motor speed with respect to input voltage is expressed as:

$$G(s) = \frac{\Omega(s)}{E_a(s)} = \frac{K_T}{(L_a s + R_a)(J s + B) + K_b K_T}$$

$$G = \frac{K_T}{[L_a]s^2 + (L_a B + R_a) s + (R_a B + K_b K_T)}$$

where  $I_a$  is armature current in Amper,  $L_a$  is Armature winding Inductance ,  $R_a$  is Armature winding Resistance,  $K_b$  is the motor voltage constant (in V/A-rad/sec) ,  $K_t$  is Torque constant and  $I_f$  is field winding current which are kept constant,  $B$  is Viscous friction constant or frictional coefficient. (N.m/rad/sec),  $T_L$  is Load Torque (N.m),  $J$  is Rotor moment of inertia (Kg.m<sup>2</sup>),  $\omega$  is the motor speed (in rad/sec) as If is constant, the machine parameter is given in table 1 is substituted into equation (6) to obtain machine transfer function (G)

$$G = \frac{2063.85}{[s^2 + 92.28s + 21.559]}$$

### (B) Fuzzy logic controller Design

The following procedures for development of Fuzzy Inference System (FIS) file;

- (i) Identification of input (crisp) variables to Fuzzy logic controller.
- (ii) Tabulation of fuzzy sets or linguistic variables with appropriate MF for input and output variables.
- (iii) Tabulation of 49 Rule base fuzzy labels for fuzzy logic controller output.
- (iv) Development of FIS file in MATLAB/SIMULINK software using FIS editor in control toolbox as MFs, Rule base statement, Selection of defuzzification method and saving the FIS file.

The reference voltage of Dc-Dc converter in this work is 500V. and the two input variables to FLC are; (1) The voltage error e(k) is expressed as;

$$e(k) = V_{ref} - V_o \quad (8)$$

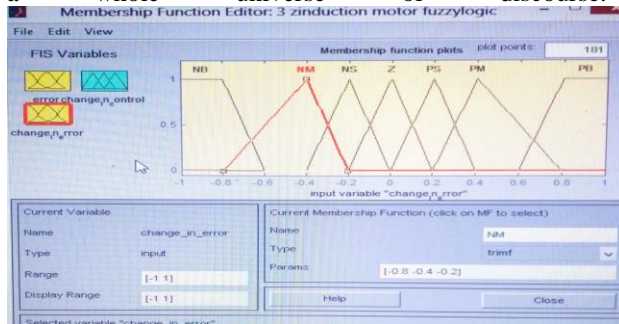
(2) Change in error or derivative of speed error is expressed as;  
 $ce(k) = e(k) - e(k - 1)$   
 (9)

The controller output called change in control is  $U_v$ . The rule base that decides the output of the inference system is derived from the 7 voltage error variables and 7 change in voltage error variables making a total of 7 x 7 or 49 rules Shown in table 2 which consists of 49 IF THEN rule that define the behaviour of the system

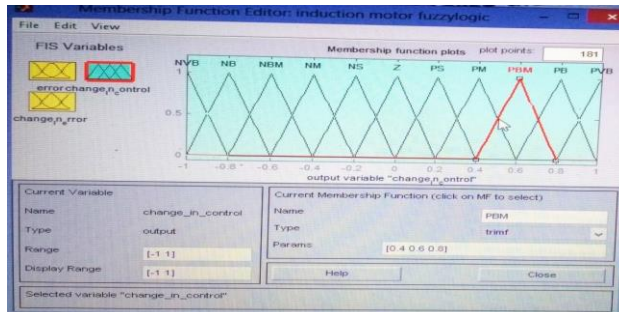
**Table 2 Fuzzy rule base table for output ( $U_v$ ) of FLC**

$e/\Delta e$	NB	NM	NS	Z	PS	PM	PB
NB	NV B	NV B	NB	NB M	NM	NS	Z
NM	NV B	NB	NB M	NM	NS	Z	PS
NS	NB	NB M	NM	NS	Z	PS	PM
Z	NB M	NM	NS	Z	PS	PM	PB M
PS	NM	NS	Z	PS	PM	PB M	PB
PM	NS	Z	PS	PM	PB M	PB	PV B
PB	Z	PS	PM	PB M	PB	PV B	PV B

The 49 IF-THEN statement of the rule base which cover a whole universe of discourse.



**Fig 1 Membership functions of input change in error( $\Delta e$ )**



**Fig 2 Membership functions of change in control ( $U_v$ )**

**(C) PWM gating signal (Pulse) Generation**

The PWM control signals are generated by comparing the obtained signal from controller with a high frequency saw tooth or carrier signal.

Dc-Dc Buck Converter average voltage is equal to the integral of the voltage waveform.

The average voltage ( $V_0$ ) is given by the following equation:

$$V_0 = D \cdot V_{max} + (1 - D)V_{min} \quad (10)$$

But usually,  $V_{min}$  equals zero and  $V_{max}$  is the supply dc voltage ( $V_s$ ) to Buck converter (Chopper)

Thus

$$V_0 = DV_{max} = DV_s \quad (11)$$

Where  $V_0$  = the average or equivalent voltage seen by the motor,  $V_s$  = the supply voltage (volts)

D= Duty cycle ratio (%),  $T_{ON}$  = Pulse duration in which Chopper switch (MOSFET) is turn ON

When  $S_1$  is ON

In state space representation

$$\dot{x} = \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_0 \\ \omega \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L} & 0 & 0 \\ 0 & \frac{-R_a}{L_a} & 0 & \frac{1}{L_a} & \frac{-K_e}{L_a} \\ -\frac{1}{C_1} & 0 & \frac{-1}{R_1 C_1} & 0 & 0 \\ 0 & \frac{-1}{C_2} & 0 & 0 & 0 \\ 0 & \frac{K_t}{J} & 0 & 0 & \frac{-B}{J} \end{bmatrix} \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_0 \\ \omega \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ 0 \\ \frac{1}{R_1 C_1} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} V_{bat} \\ T_L \end{bmatrix} \quad (12)$$

$$y = [0 \ 0 \ 0 \ 0 \ 1] \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_0 \\ \omega \end{bmatrix} = \omega \quad (13)$$

(13)

When  $S_2$  is ON

In State Space representation

$$\dot{x}_2 = \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_0 \\ \omega \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L} & \frac{-1}{L} & 0 \\ 0 & \frac{-R_a}{L_a} & 0 & \frac{1}{L_a} & \frac{-K_e}{L_a} \\ \frac{-1}{C_1} & 0 & \frac{-1}{R_1 C_1} & 0 & 0 \\ \frac{1}{C_2} & \frac{-1}{C_2} & 0 & 0 & 0 \\ 0 & \frac{K_t}{J} & 0 & 0 & \frac{-B}{J} \end{bmatrix} \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_0 \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{R_1 C_1} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} V_{bat} \\ T_L \end{bmatrix} \quad (14)$$

$$y = [0 \ 0 \ 0 \ 0 \ 1] \begin{bmatrix} i_L \\ i_a \\ V_1 \\ V_0 \\ \omega \end{bmatrix} = \omega \quad (15)$$

The Bidirectional dc-dc converter switches from buck mode to boost in bidirectional way

#### (D) Design of Closed Loop Electric Vehicle Drive System

The designed EV motor drive system comprised of four sections such as battery, bi-directional dc-dc converter, Fuzzy Logic controller and dc machine. The half bridge dc-dc converter topology is selected to control the dc motor. Battery is taken as low voltage source and PMDC motor is considered as the high voltage load whose speed has to be controlled.

The control of the EV battery charge is achieved by controlling the bidirectional converter with Fuzzy logic controller. In this feedback control technique, the error signal going to Fuzzy logic controller is obtained by comparing the reference motor terminal voltage ( $V_{ref} = 500V$ ) with converter output voltage ( $V_o$ ). The FLC sends command signal to PWM generation block. The PWM control signals are generated by comparing the obtained signal with a high frequency saw tooth signal. the starting voltage of battery is set to 380 V and the operating voltage of dc machine used in traction system is 500Vdc. The battery is discharged when dc machine has started acceleration in motoring mode as the converter is in boost mode and the converter boost the output voltage to 500v for the motor. When the battery voltage and State of Charge (SOC) level drops below 360v, the Bidirectional converter switches to buck mode and machine is in regenerating mode and the machine is now supplying voltage to the battery. consequently, battery voltage and SOC level is increased as battery starts charging. The Fuzzy logic controller determines duty cycle of the two Power Switches (MOSFETS) in the

dc-dc converter to control charge and discharge of battery during Motoring mode and Regeneration mode. The dc-dc Bidirectional converter system model control was implemented in the Simulink as the model was simulated. The simulation has been done for a total time of 8 sec with the dc-dc bidirectional converter works in boost mode (motoring mode) for the initial period as it supplies boost voltage to dc machine. And After 2 sec motor operates in regenerative mode (Buck mode) and a negative torque has been applied on the motor for next 5 seconds so as to realize the vehicles downhill motion. The converter operates in buck mode during regeneration thus transferring the electrical energy from the motor to the battery.

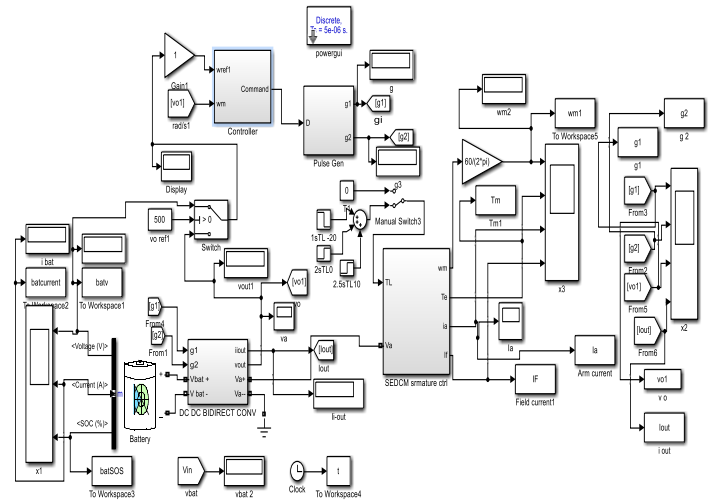


Fig 3 Simulink Model of Dc-Dc Bidirectional Converter for Electric Vehicle drive System

### III. SIMULATION RESULTS AND DISCUSSION

In order to dynamically predict the control topology, SIMULINK toolbox in MATLAB/SIMULINK software program is used for the simulations to produce a number of results with respect to important variables of the dc machine. In this section, the various waveforms corresponding to the motor speed, armature current, SOC, battery voltage and the battery current during simulation are presented in subsequent plots. The simulation has been done for a total time of 7 seconds with the converter working in buck mode (motoring mode) for the initial period. After 2 seconds the converter operates in boost mode (motor operates in regenerative mode) as negative torque (-10Nm) is

applied on the motor so as to realize the vehicles downhill motion.

### Pulse Waveform

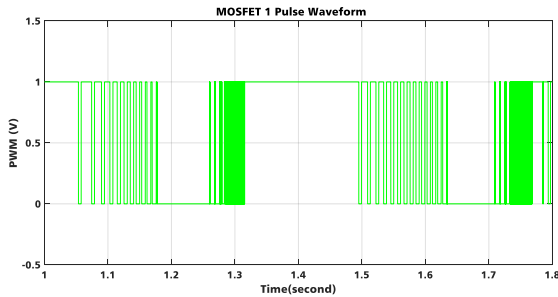


Fig 4.1: Pulse waveform for power switch (MOSFET 1) in Boost mode

This shows the duration in which the Dc-Dc bidirectional converter MOSFET 1 (power switch) is at ON state and the system operate at boost mode and energy is transferred from battery to dc motor (motor mode)

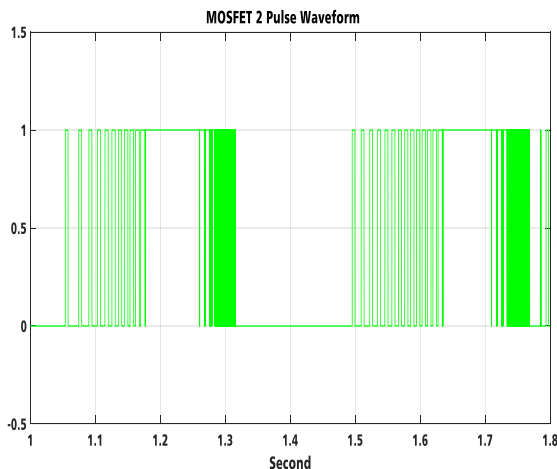


Fig 4.2 pulse waveform for power switch (MOSFET 2) in Buck mode operating at switching frequency of 25KHz

Figure 4.2 shows the duration in which the Dc-Dc bidirectional converter MOSFET 2 (power switch) is at ON state and the system operate at buck mode and energy is transferred from dc machine to battery (regeneration mode).

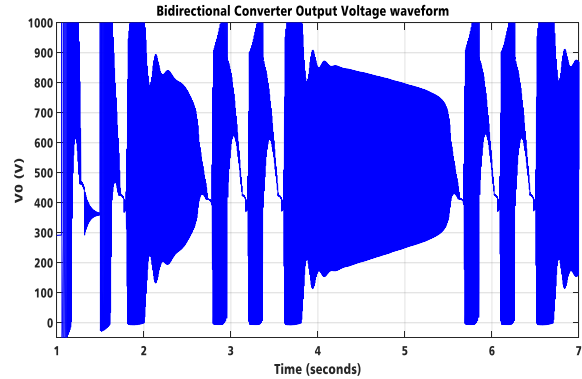


Fig 4.3: Converter Output Voltage (High Voltage Side) Figure 4.3 depicts the Output Voltage waveform of the Dc-Dc bidirectional converter as the system operate in both boost mode and buck mode. energy is transferred from battery to dc machine and dc machine to battery to maintain certain charge level of the battery. The boost voltage waveform in forward direction to the dc machine have average value of 500v which is rated armature voltage value and at interval between (1.2 to 1.5 second) where the converter is on buck mode as machine supply energy to battery, the average output voltage drops to 290v and increases during boost mode operation.

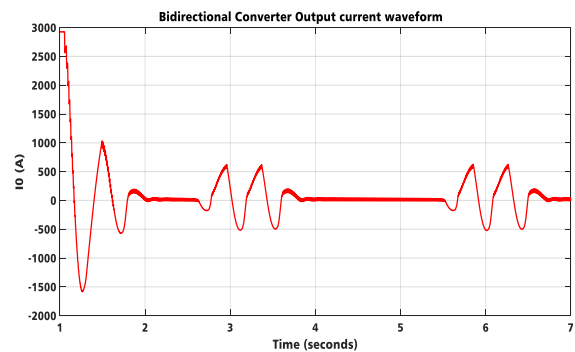


Fig 4.4 Bidirectional Converter output current Response

Fig 4.4 depicts Bidirectional Converter output current response; current value increases during boost mode as battery supply power to machine. And during buck mode the current values goes negative i.e Charging current since the battery is charged by the Bidirectional converter during this period. The ripple on the current response at 3 and 6 seconds is due to change in load torque condition.

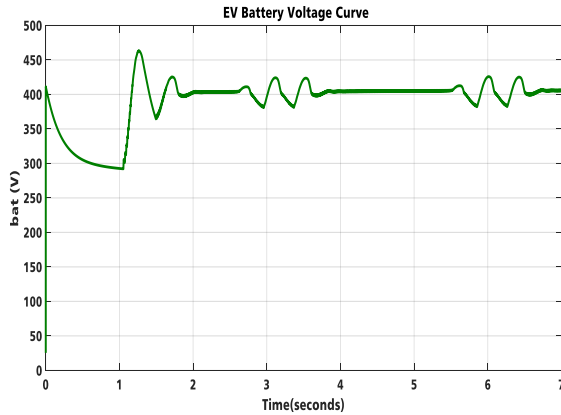


Fig. 4.5 Battery Voltage or Input voltage level response (Low Voltage Side).

Figure 4.5 depicts the battery Voltage waveform as the system operate in both boost mode and buck mode. From start, battery voltage decreased as energy is transferred from battery to dc machine from start time to 1.2 second and thereafter energy moves from dc machine to battery to maintain certain charge level of the battery. Battery lithium-ion initial voltage level is 380v with capacity of 100Ah, and State of Charge of 85% from 1.2 seconds the voltage level is increased to 450v due to charging and later settled at 400v after 2 seconds.

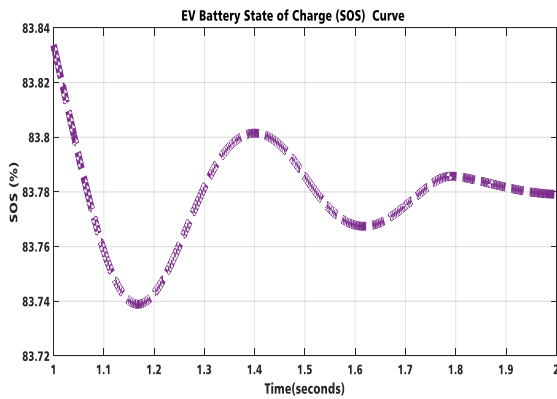


Fig 4.6 Battery State of Charge level Response

From the start of the simulation time to 1.2 second when the converter operate in boost mode I.e during motoring mode, the battery SOC (state of charge) decreases from 85% to 83.7% as the battery is providing the power to the motor and it increases from after when the converter switches to buck mode when the machine is in regeneration mode, as battery charges started rising from 1.23second at 2 seconds when the motor speed stabilizes, the charge level is maintains at 83.78%.

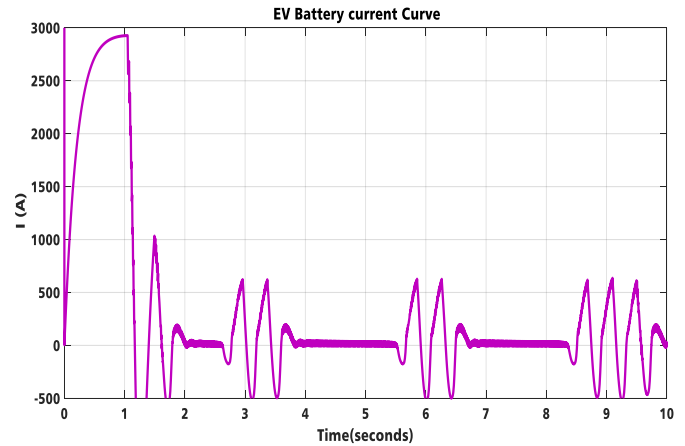


Fig 4.7 Battery current level Response

Fig 4.7 depicts Electric Vehicle battery current response, current value increases from start during boost mode as battery supply power to machine as voltage drops to maintain constant power and stabilizes at 19.5 A after 2 seconds when machine speed stabilized. And during buck mode from 1.2 to 1.5 second, the current values increase as the battery is charged by the Bidirectional converter during this period.

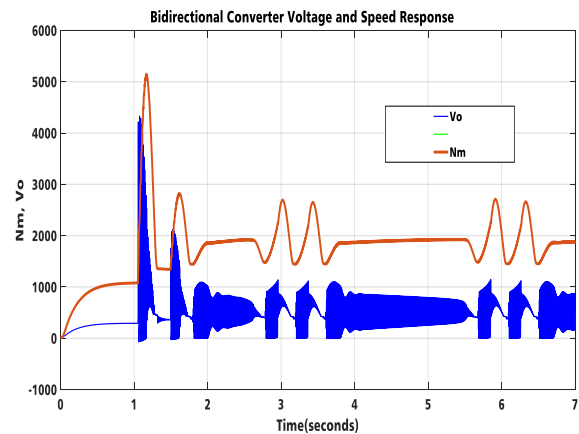


Fig 4.8 Dc Machine Speed and armature voltage Response

Fig 4.8 shows speed response and armature voltage response from converter. speed increases when the converter is working in boost mode as the machine is operating on motoring mode for the initial 1.2 second. After 1.2 second, the converter operates in buck mode as the motor at this instant operates in regeneration mode thus transferring the electrical energy from the motor (high Voltage side) to the battery (low Voltage side). a negative torque (-10Nm) has been applied on the motor for next 4 seconds. From the figure, speed of the machine depends directly on average value of armature voltage

supplied (Boost output voltage from the converter), when the converter operates in buck mode, the average output voltage drops and consequently led to decrease in machine speed.

#### IV CONCLUSION

This Work covers modeling and control of DC-DC bidirectional converter for Electric Vehicle (EV) drive system which operates in buck and boost modes. The initial state of battery charge is set at 85% where the discharge current is 19.5 A during motor mode. The nominal voltage of battery stack is 380 V with maximum capacity of 100 Ah. The rated power of dc machine is 250 HP with 500 V armature voltage and 300 V field voltage. The operating mode of power converter is determined according to the torque values of dc 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 bi-directional dc-dc converter is controlled with fuzzy logic controller in both modes. The performance of the circuit is verified in Simulink using MATLAB/SIMULINK software. From Simulation result verification, it shows that the proposed converter with Fuzzy logic controller is effective and efficient in charging process and EV drive speed regulation and it's recommended for all-electric vehicle.

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