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Simulation of a Regenerative Braking Method for Brushless DC drives with ultra capacitor based energy recovery system

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Abstract – Electric and hybrid-electric vehicles are capable of providing electrical braking to assist mechanical brakes. They efficiently add energy to the energy storage system, extend driving range and improves the overall efficiency of the system. An efficient regenerative Braking strategy adapted to brushless dc motor is proposed. This method employs independent switching in conjunction with pulse width modulation (PWM) during regeneration. Motor control employs a combination of improved fuzzy control and PI control for effective braking. Ultra capacitor voltage, and brake strength are chosen as the input variables of fuzzy control, fuzzy control is used obtain a precise brake current. PI control adjusts the BLDC motor PWM duty to obtain the constant brake torque. A combination of both control enable the smooth transitions and efficient braking operation. A new energy storage system ESS, includes both batteries and ultra capacitors (UCs) is also proposed. This improves the regenerative energy recycling efficiency of electric and hybrid electric vehicles considerably. The Proposed Regenerative Braking system has the ability to recover energy and ensure the safety of braking for vehicular applications

INTRODUCTION

There is a rapid development of the world-wide automobile industry, Use of IC engine worsen air quality and causes serious environmental problems. Hence research and development of a non-polluting transport or even a low polluting transport has become an increasingly relevant topic. Electric vehicles which is also known as green vehicle due its zero emission to the air, ie there are no toxic gases produced during the operation of electric vehicle which increases its suitability to IC Engines. Electric vehicle is an effective and promising alternative. Recycling of brake energy by employing the methods of regenerative braking is can be also realized in an electric vehicle which is not possible in conventional ICE vehicles. In regenerative braking, the motor, will work as a generator during braking, inertial energy generated is converted into electrical energy which can be stored in electric storage devices like battery ultra capacitors etc and can be reused efficiently. The motor braking torque experienced during the process results in the slowdown and stoppage of the vehicle. Use of regenerative braking helps in increasing the driving range of the vehicle. It is observed that a vehicle with Regenerative Braking system can increase the driving range up to 15 percent comparing to that of an EV without one. [1] Battery performance can be adversely affected by the high current generated during braking this could even reduce its life. A solution to this problem is to use connect the battery through a DC/DC converter through an ultra capacitor bank and store the braking energy to an ultra capacitor. This system can store instantaneous large currents quickly and ensures compete recovery of brake energy. [6]

II. COMPONENTS OF THE SYSTEM

The main components of system includes the drive motor , Electronics commutators, Energy storage system including battery and ultra capacitor and employs complimentary switching method to connect each to system during motoring and regeneration respectively. Motor control employs fuzzy and PI control, Boost converter is used for transfer of energy stored during regeneration.

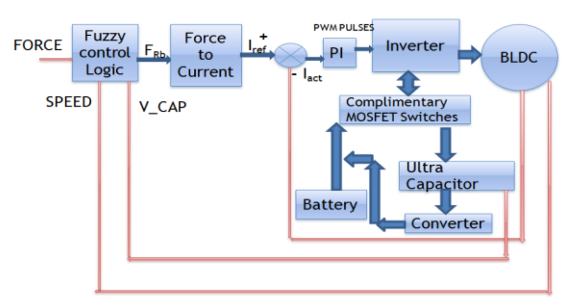

Fig 1: Proposed system

A. Drive Motor

Electric drives are the key element for EVs and HEVs. The main characteristics of electric drive which can be employed in EV applications are as follows. They should have high power and torque density, wide spectrum of speed range, constant-power operating capacity, Should meet high torque demand during starting, hill climbing, overtaking etc, during overtaking it should be able to provide high intermittent overload capability. Should be reliable and robust. Invention of high-energy permanent-magnet (PM) Materials made the construction of high efficient permanent magnet motors possible. PM brushless (BL) drives with its control strategies have been identified to provide the above mentioned characteristics required for the operation of modern Electric and hybrid electric vehicles [3]

B. BLDC Motor

BLDC motor is a type of synchronous motor. ie stator and rotor magnetic field rotate in synchronism and has no slip. In a BLDC motor, rotor has permanent magnets, and stator has a laminated steel core on which the star connected armature windings are fixed. Opposite pairs of pole windings and excited and sequentially to obtain rotation. Rotor position is derived from the Hall Effect sensors which are mounted on the motor shaft.

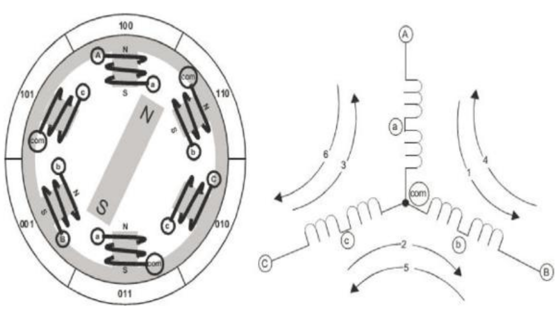

Fig 2: Star connected BLDC motor

The electrical and mechanical mathematical equations of BLDC are:

$$
\begin{aligned}
Va &= RIa + (L-M)\frac{dIa}{dt} + Ea \\
Vb &= RIb + (L-M)\frac{dIb}{dt} + Eb \\
Vc &= RIc + (L-M)\frac{dIc}{dt} + Ec
\end{aligned}
\qquad (1)
$$

Back emf equations of the three phases are as follows,

$$
\begin{aligned}
Ea &= Ke\omega F(\theta) \\
Eb &= Ke\omega F(\theta - \frac{2\pi}{3}) \\
Eb &= Ke\omega F(\theta + \frac{2\pi}{3})
\end{aligned}
\qquad (2)
$$

State space forms of equations of BLDC motor are

$$
\begin{bmatrix} Ia \\ Ib \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{R}{L} & 0 & 0 \\ 0 & \frac{R}{L} & 0 \\ 0 & 0 & \frac{R}{L} \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ \frac{1}{3L} & \frac{-1}{3L} & 0 \\ 0 & 0 & \frac{1}{j} \end{bmatrix} \begin{bmatrix} Vab - Eab \\ Vbc - Ebc \\ Te - Tl \end{bmatrix} \qquad (3)
$$

$$
\begin{bmatrix} Ia \\ Ib \\ Ic \\ \omega \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ \omega \end{bmatrix}
$$

Where

V_k= k_{th} Phase Voltage applied from inverter to BLDC.

I_k = k_{th} Phase Current.

R = Resistance of each phase.

L = Inductance of each phase

M = Mutual Inductance

E_k = k_{th} phase back emf

Ke = Back emf constant

ω = Speed of rotor

T_e= Electric Torque

T_l= Load Torque

A. Electronics Commutators

DC supply of three phase inverter is usually provided by a dc battery. It has six switches, switches which can be a thyristor, an IGBT or MOSFET. These switches turned ON or turned

OFF by using external control. Each step is of sixty degree duration for a six step inverter. These switches sequence are determined by the output of Hall Effect sensors and each switch is gated at 60 degree interval in correct sequence which produce a 3 phase AC as inverter output. [2]

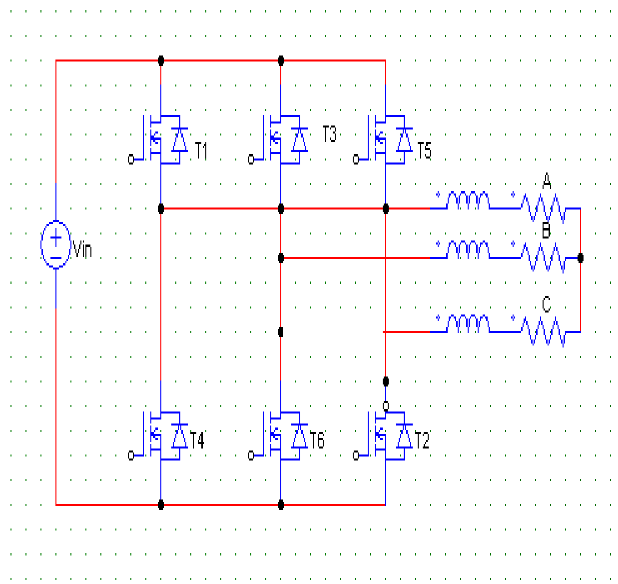

Fig 3: A typical H bridge inverter

A. Energy storage system

Energy storage systems used primarily include battery and Ultra capacitor. Battery powers the circuit during motoring and ultra capacitor stores energy during regenerative braking. ESS system which has both batteries and ultra capacitors (UCs), can be widely used in hybrid electric vehicle (HEV) and electric vehicle (EV) applications. A battery is used to power electric vehicles, Rechargeable battery or secondary battery is usually used for this purpose. The most important aspects of EV batteries are capacity, range charging. Capacity is measured mainly in Ampere hours. Time taken for charging depends on its size and charger voltage. Range is the drivable distance. Lead-acid batteries can be used in electric vehicle primarily due to their mature technology, high availability, and low cost Ultra capacitor is utilized only during regeneration The UC connection methodology highly expands the efficiency of regenerative braking system. The main component of ultra capacitor based systems is the DC-DC converter which is connected in parallel with the battery. Regenerative energy charges the capacitor and converter is worked in boost mode to transfer energy to the supply [5]

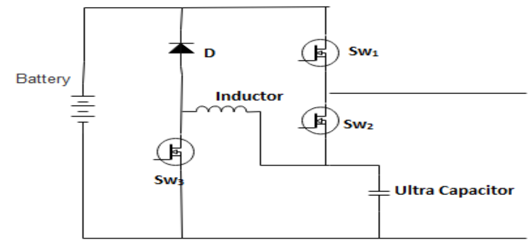

Fig 4: Battery Ultra capacitor interface

III. MOSFET CONTROL FOR REGENERATION

The basic drive circuit consists of a six step inverter circuit. Each motor lead is connected to the high side and low side switches. The switches S1, S3, S5 are the high side switches and S2, S4, S6 are low side switches. The main function of the inverter is to provide Electronic commutation of the BLDC Motor, order of conduction on the inverter switches are controlled to obtain the commutation of the inverter. Figure 5 shows typical H Bridge converter for BLDC Motor

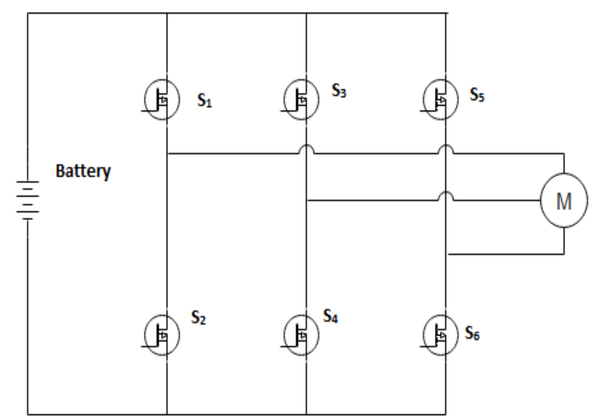

Fig 5: H bridge converter for BLDC Motor

Switching sequence for rotation of motor is derived from the output of Hall Effect sensors as shown in Figure: 6

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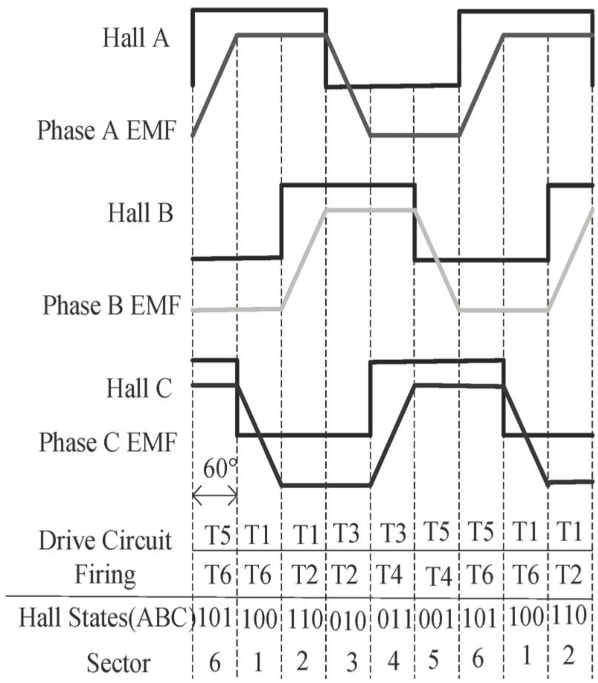


Fig 6: Switching Sequence for motoring

A. Brake strategy for Regeneration

During Regeneration the switching sequence is changed to reverse the direction of current to the motor-Ultra capacitor system. Effective brake control is obtained by turning off the upper switches and lower switches are gated in PWM. Regenerative braking is obtained by operating a single switch in a leg. Inductance of the motor winding is utilized to increase the voltage and by proper controlling of the MOSFET switches, motor constitute a boost circuit which produces the necessary regenerative braking

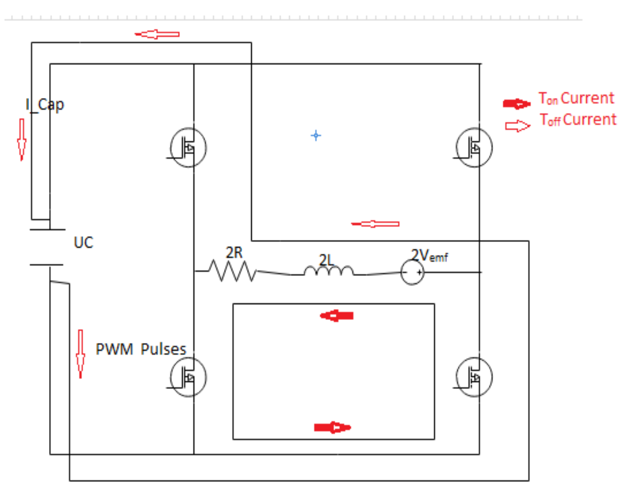


Fig 7: Regenerative braking with single switch.

When Brake signal is obtained fuzzy logic controller determines the value of regenerative brake force. Brake current is obtained from Brake force through

$$I_{regen} = kF_{regen} \qquad (4)$$

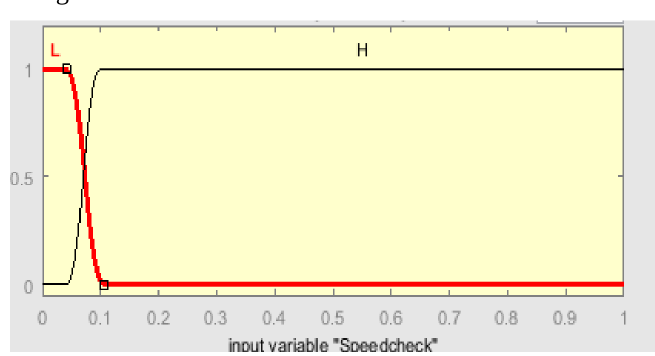
I_{regen} is the regenerative brake current which is proportional to regenerative Brake force F_{regen} and k is the scaling factor According to the theory of charge balance.

$$\int_{t}^{t+T_s} i_{dc}dt = DT_s\frac{-V_{dc}}{R_b} + D'T_s(i_a - \frac{V_{dc}}{R_b}) \qquad (5)$$

Where D is the duty cycle satisfying D+D' = 1

B. Fuzzy control

Amount of energy regenerated is a depended on multiple factors. Hence fuzzy logic control strategy is used for deriving the reference brake current. Fuzzy logic controller has three input speed of the vehicle, Brake force and Voltage on the capacitor. Input variables of the fuzzy are brake force, voltage across ultra capacitor, and speed the system, output variable comprises of the ratio of regenerative braking which can be obtained. Brake force can be classified as low medium and high. Speed is classified as Low and High speeds. Universe of discourse of the three input variables are [0 1] defined over their respective per unit value. When the speed is low regenerative braking will be low and when the speed is at its highest, maximum amount of regeneration can be obtained. Output variable is the ratio of output variable include {mf_0, mf_1, mf_2, mf_3, mf_4, mf_5} the membership functions are shown in Figure 8



(a)Speed

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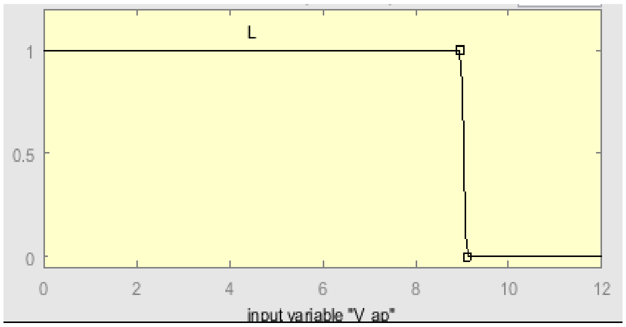
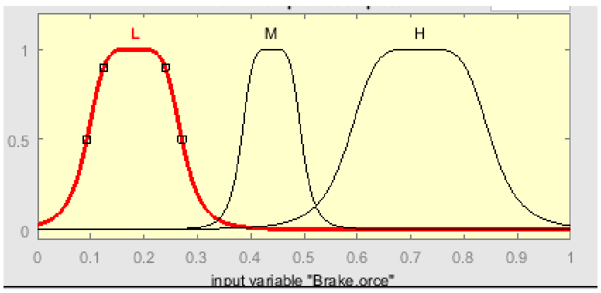
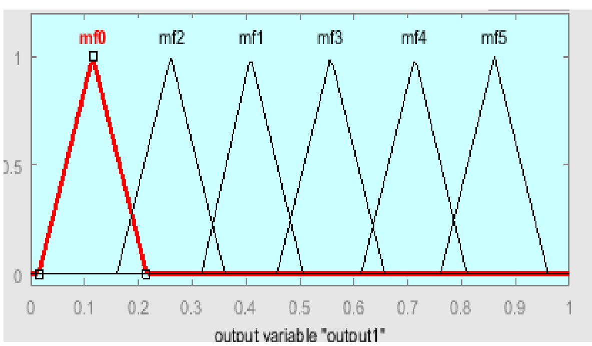


(b) UC Voltage



(c) Brake Force



(d) Output

Fig 8: Fuzzy membership function. (a) Membership functions of speed. (b) Membership functions of capacitor voltage. (c) Membership functions of brake force. (d) Membership functions of ratio Fuzzy control rules: the braking force is L, M, and H; Vcap is L, and speed is L and H.

I: Fuzzy logic control rules

SPEED	V_CAP	BRAKE FORCE	OUTPUT
L	L	L	Mf0
L	L	M	Mf1
L	L	H	Mf2
H	L	L	Mf3
H	L	M	Mf4
H	L	H	Mf5

IV. SIMULATION

Regenerative braking system of electric vehicle was modeled under MATLAB and Simulink environment. Motoring and regenerative braking were simulated and results verified. Simulation time was 8.5 sec with 5 sec of motoring, 1.2 sec braking and 1.4 second of motoring

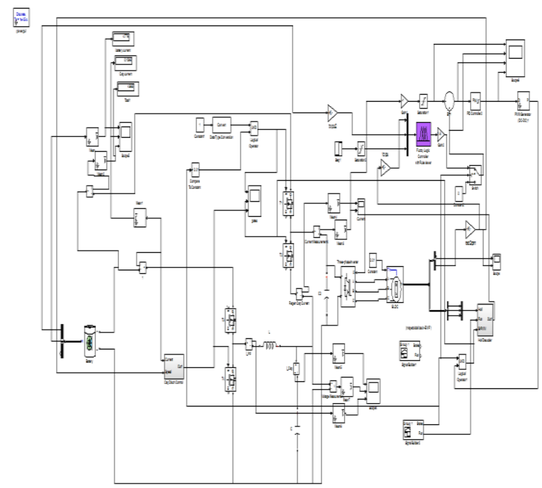


Fig.9 MATLAB/SIMULINK Model for proposed system

In the MATLAB/Simulink the following motor parameters were used Pe = 50 W, Input Voltage = 24 V, Rated speed = 4000 rpm, Back E.M.F = 3.7699 V/krpm , Phase Resistance = 0.36 Ω , Phase Inductance = 0.6 mH.

Boost DC-DC Converter parameters,

Switching Frequency = 25 kHz, Ultra Capacitor (C) =.6 F, Inductor (L) = 5mH

RESULTS AND DISCUSSIONS

Initially motor was operated in motoring mode by applying run signal for 5 sec. Brake signal was applied at 5 sec till 7.2 sec and current direction reverses and run signal is applied after braking to bring back the motor to running condition

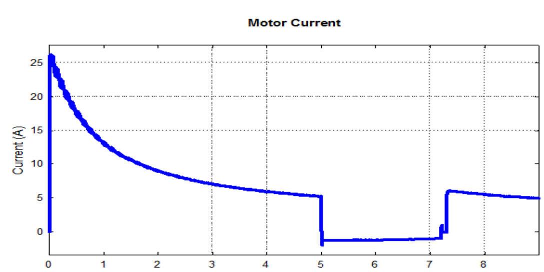


Fig 9: Motor current Vs Time waveform

Capacitor current is positive during regenerative braking after braking Energy stored in capacitor is transferred to supply and capacitor current reverses and becomes negative as shown in Fig 10

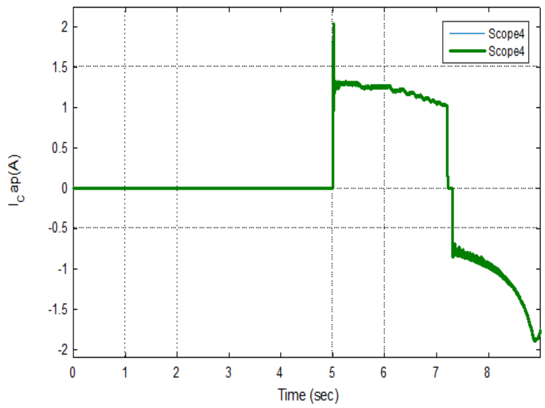


Fig 10: Motor current Vs Time waveform

Capacitor charges during regeneration mode and voltage increases. When capacitor voltage reaches set value (4.6V) boost converter is gated on and capacitor discharges and as a result Voltage across capacitor decreases and current flow through inductor to the supply as shown in Figure 11 and figure 12 respectively.

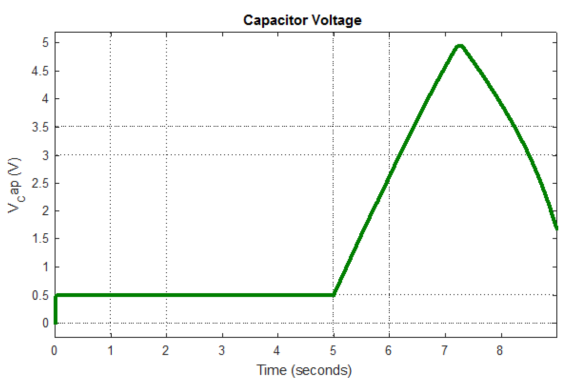


Fig 11: Capacitor Voltage Vs Time waveform

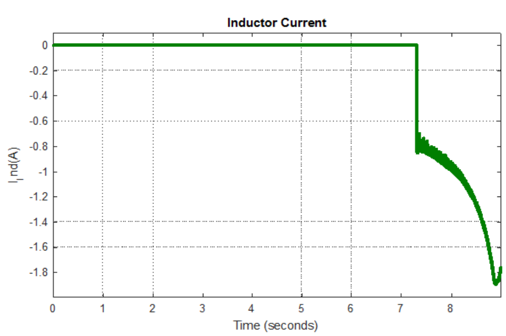


Fig 12: Inductor current Vs Time waveform

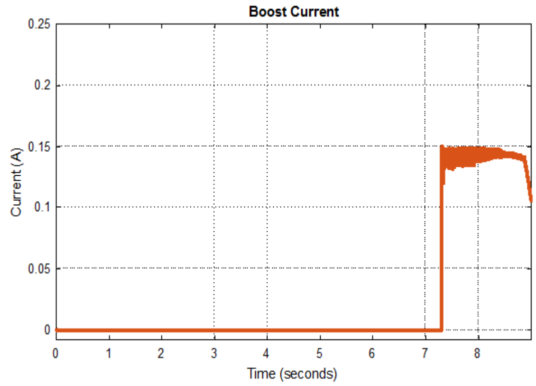


Fig 13: Boost current Vs Time waveform

CONCLUSION

Regenerative braking system for BLDC fed Electric vehicle has been realized and performance of the EV regenerative brake has been verified using simulations. Independent switching of lower switches in combination with pulse width modulation (PWM) is used for realizing regeneration and to implement an effective braking control. Ultra capacitor used to store brake energy improves the regenerative energy recycling efficiency considerably. Control s combination fuzzy control and PID control to realize efficient braking. Braking force is affected by many influences such as Ultra capacitor voltage, speed, brake strength considered in the design of efficient RBS system. These three factors are chosen as input variables for fuzzy control, output of fuzzy control gives the amount of regenerative braking and the precise brake current is obtained. PI control adjusts the BLDC motor PWM duty to obtain the constant brake torque. PI control is faster than fuzzy control, so the two methods combined together can realize the smooth transitions. The proposed RBS system has the ability to recover energy and ensure the safety of braking in different situations prolongs the driving distance, has better performance robustness, and efficiency.

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REFERENCES

[1] Xiaohong Nian, Fei Peng, and Hang Zhang, "Regenerative Braking System of Electric Vehicle Driven by Brushless DC Motor," IEEE Trans. on Industrial electronics, vol. 61, no. 10, October 2014.

[2] C. Sheeba Joice, S. R. Paranjothi, and V. J. Senthil Kumar, "Digital control strategy for four quadrant operation of three phase BLDC motor with load variations," IEEE Trans. Ind. In format, vol. 9, no. 2, pp. 974–982, May 2013..

[3] J. M. J. Yang, H. L. Jhou, B. Y. Ma, and K. K. Shyu, "A cost-eective method of electric brake with energy regeneration for electric vehicles," IEEE Trans. Ind.Electron., vol. 59, no. 12, pp. 46014616, Dec. 2012

[4] M. Cheng, W. Hua, J. Zhang, and W. Zhao, "Overview of stator permanent magnet brushless machines," IEEE Trans. Ind. Electron., vol. 58, no. 11, pp. 5087–5101, Nov. 2011.

[5] K. Yoong, Y. H. Gan, G. D. Gan, C. K. Leong, Z. Y. Phuan,B. K. Cheah, and K. W. Chew, "Studies of regenerative braking in electric vehicle," in Proc. IEEE Conf. Sustainable Utilization Develop. Eng.Technol., Nov. 20/21, 2010, pp. 40–41..

[6] Shuai Lu, Keith A. Corzine, "A New Battery Ultracapacitor Energy storage system design and its motor integration for Hybrid electric vehicles" IEEE Trans. on Industrial electronics, vol. 61, no. 10, October 2007.

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