Advanced Hybrid Electric Vehicle (HEV) dynamics: Integrating IC engine, fuel Cell, battery and EDLC using flux-DC converters

S G Srivani[1], **V Srinivasulu**[2]

[1]Electrical and Electronics, RV College of Engineering, Bengaluru, India
[2]Electrical and Electronics, RV College of Engineering, Bengaluru, India

***

Abstract - *Hybrid Electric Vehicles (HEVs) are revolutionizing electromobility, merging advanced tech with eco-conscious design. As leaders in sustainable transport, they drive decarbonization and break free from fossil fuel dependence. The orchestrated amalgamation of energy from electrochemical batteries, Fuel cells, Internal Combustion Engines (IC's), EDLC's and regenerative braking systems, the vehicles attain unprecedented levels of energy autonomy and adaptability. Leveraging sophisticated powertrain modulation techniques and intricate energy optimization algorithms, HEVs navigate a myriad of dynamic driving terrains, optimizing energy flux while mitigating adverse environmental impacts. By harnessing cutting-edge flux additive converters, High current density DC-DC converters and Bi-directional converters, the system efficiently manages power flow, this seamless integration enhances overall performance, enabling more effective control of hybrid power sources. the Field oriented control (FOC) algorithm is used for controlling the BLDC motor, this study serves as a guiding beacon, illuminating the transformative potential inherent in the amalgamation of IC engine with Fuel cell. This propels HEVs into an epoch characterized by unparalleled efficiency and sustainability, thus heralding a significant paradigm shift in the automotive landscape towards a greener and more sustainable future. This postulate is substantiated through an intricate simulation conducted by utilizing the MATLAB environment.*

Key Words: Hybrid Electric Vehicle(HEV), Lithium-ion battery, EDLC, Flux-additive DC-DC converter, IC engine, High-Flux additive DC-DC converter, BLDC motor.

1.INTRODUCTION

Electrifying the road ahead involves a quest for sustainable mobility through Electric Vehicles (EV's) and Hybrid Electric Vehicles (HEV's). Amid a world grappling with the environmental toll of traditional transportation. Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) stand as beacons of innovation and sustainability [1],[2]. With their silent engines and zero-emission promise, EVs lead the charge towards a cleaner, greener future, while HEVs offer a seamless transition, blending electric power with conventional engines for enhanced efficiency. Electric vehicles (EVs) harness electric motors fuelled by rechargeable batteries, presenting a sustainable alternative to traditional combustion engine vehicles, thereby mitigating environmental impact and advancing energy efficiency in the transportation landscape [3].

The demand for electric vehicles arises from their capability to mitigate emissions, decrease dependency on finite fossil fuels, foster technological innovation, and harmonize with global initiatives to combat climate change. Together, they represent a transformative force reshaping the automotive landscape and driving us towards a more sustainable tomorrow. In today's world, personal transportation is the lifeblood of economic and social development, with millions of vehicles traversing the globe daily. Yet, this convenience comes at a cost – a heavy reliance on fossil fuels. With over 800 million cars worldwide and a staggering 250 million in the United States alone, the strain on Earth's resources is undeniable. As China surpasses the United States to become the world's largest auto market, the trajectory of personal vehicle ownership is set on an unstoppable course. However, the path we've chosen is fraught with challenges.

The system has been implemented with multi-energy sources, the internal combustion engine is combined with the battery, fuel cell and EDLC (Electric double layer capacitor) system, the EDLC has been integrated with a bidirectional converter, the High flux density and flux-additive DC-DC converters are unidirectional converters, the EDLC has been specifically connected to a bidirectional converter so that it can get recharged quickly since the power density of the EDLC is high, around 10 KW/kg. The battery system does not undergo charging during regenerative braking action since it has low power density, around 2 KW/Kg, but has high energy density, around 170 Wh/Kg, hence it is used as an energy storage system [4]-[5].

The Brushless DC (BLDC) motor is controlled by Field -oriented algorithm technique, the Indian drive cycle (IDC) has been designed to test the proposed system, the IDC provides the reference velocity to the longitudinal driver, which generates the acceleration command, the acceleration command is the Iref to the FOC controller, the pulses generated by the FOC controller is fed to the IGBT switches of the three phase-inverter.

The FOC algorithm's principal function involves comparing Iq* with the instantaneous I stator quadrature (Iq) value necessitating an accurate computation of the latter. This computation is facilitated by the transformation of the three-

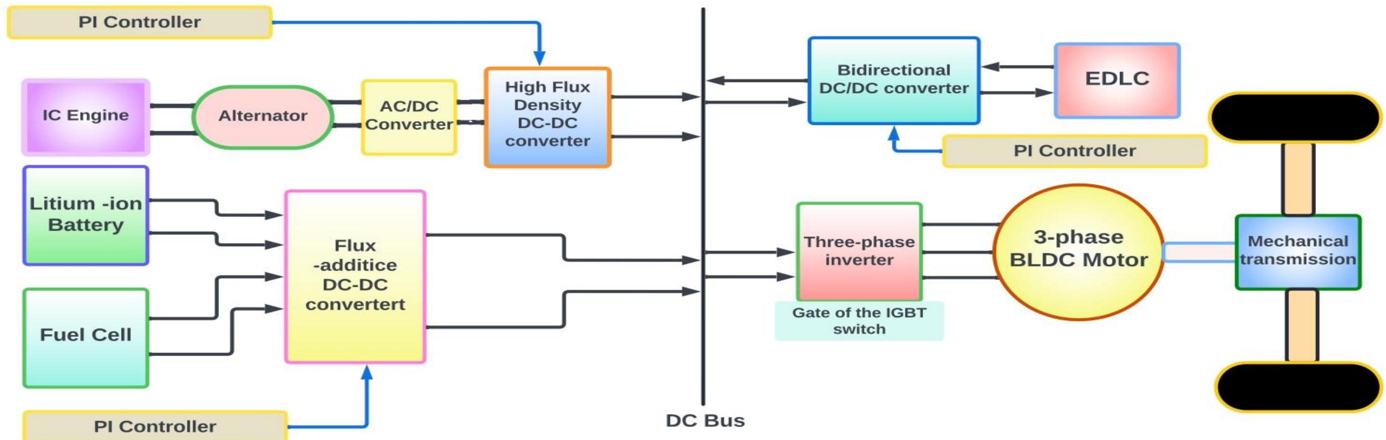

Fig -1: Architecture of the proposed system

phase stator currents (Iabc) into a two-phase orthogonal stationary reference frame (Iαβ) via the Clarke transform, Subsequently, the Park transform is employed to transpose the Iαβ components into the rotating reference frame currents (Idq). This intricate control methodology meticulously synchronizes the motor's electrical and mechanical subsystems, fostering optimal performance across both dynamic and steady-state operational regimes. Hybrid Electric vehicles (HEVs) epitomize a disruptive paradigm shift in transportation, leveraging electric motors and rechargeable EDLCs to supplant the conventional reliance on fossil fuels inherent in internal combustion engine vehicles. Ultimately, this exhaustive inquiry furnishes critical insights for policymakers, industry stakeholders, and consumers, guiding strategic decision-making processes and charting a course towards a sustainable and resilient electric mobility paradigm. The architectural blue print of the proposed system has been illustrated in Figure 1.

2. Flux-additive DC-DC converter integrating Li-ion battery and fuel cell to the DC bus

The architectural schematic of the multi-input flux additive DC-DC converter, as delineated in Figure 2, integrates a plethora of indispensable elements, each pivotal to the converter's functionality.

2.1 Initial Input-Stage Circuit

This phase encompasses the primary winding of transformer T1, characterized by N1 turns. The current Is1 traversing this winding generates a magnetic flux Φ1, resulting from the intricate interplay between the electrical current and the winding's inherent magnetic field.

2.2 Secondary Input-Stage Circuit

This segment incorporates the primary winding of transformer T2, consisting of N2 turns. The current Is2 flowing through this winding engenders a magnetic flux Φ2, following the fundamental principles of electromagnetic induction.

2.3 Output-Stage Circuit

The current Is3 passing through this winding produces magnetic flux Φ3, which is crucial for the converter's energy transfer mechanism.

2.4 Transformer

As current traverses the primary winding with N1 turns, it establishes a magnetic flux that induces an electromotive force (emf) in the secondary winding with N2 turns, in accordance with Faraday's Law. The schematic block diagram is depicted in figure 2.

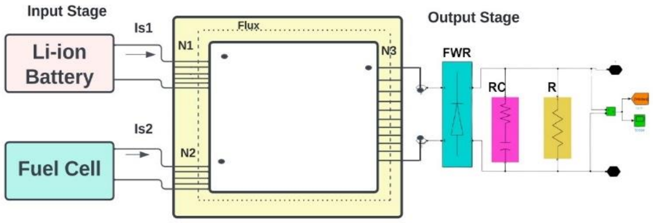

Fig -2: Schematic of Flux Additive DC-DC Converter

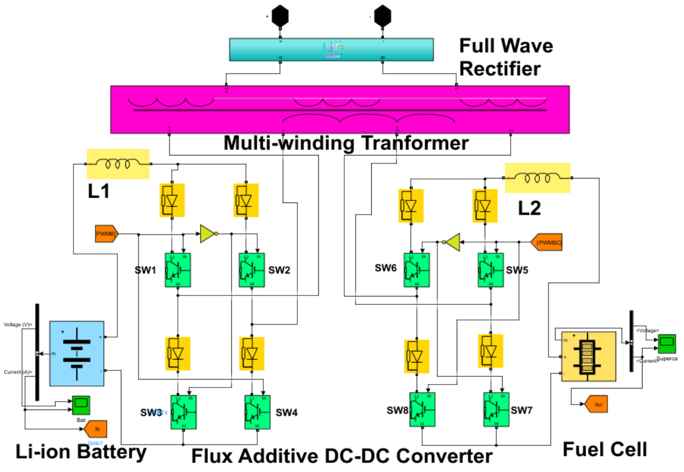

Fig -3: Simulink diagram of Flux-additive converter

Table -1: Design specifications of cutting-edge flux additive DC-DC converter

S.NO	Parameter	Value
1	L1	1 mH
2	L2	1 mH
3	RC	1000 µC, 1 mΩ
4	R	2.88 Ω
5	V1	48 V
6	V2	48 V
7	Vout	245 V

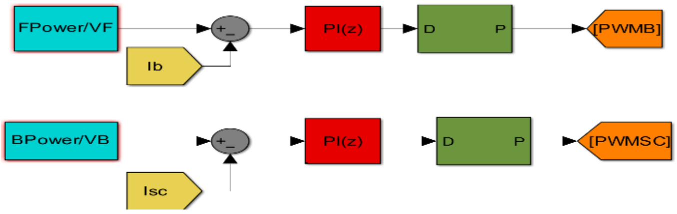

Fig-4: PI controller for optimizing performance of the flux additive DC-DC converter.

3. HIGH CURRENT DENSITY DC-DC CONVERTERS FOR IC ENGINES

Figure 4 shows a high flux density DC-DC converter connecting an IC engine to a three-phase inverter for an EV. The LCL network filters power and reduces THD, while diodes D5 and D6 regulate AC flow, producing a refined DC output. MOSFETs M1 to M4 control voltage, with L1, L2, and C1 ensuring efficient energy storage and delivery.

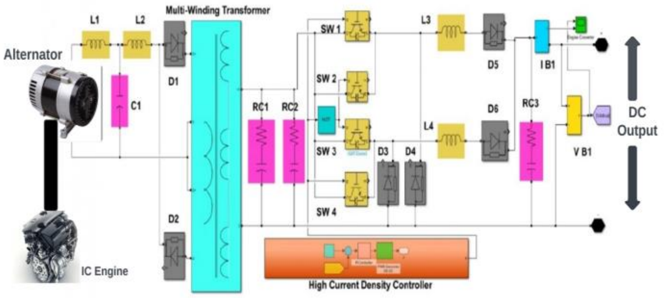

Fig -5: Simulink diagram of High current density DC-DC converter DC-DC converter interfaced with IC engine

The High DC-DC converter exhibits four operational modes:

3.1 Mode 1 (0 < t < DTs): IGBTs 1 and 3 are in conduction, while IGBTs 2 and 4, along with Diodes D3 and D4, remain non-conductive. The corresponding inductor voltages are expressed as VL1 = V2 - Vo and VL2 = V2 - Vo.

3.2 Mode 2 (DTs < t < Ts): All IGBTs (1, 2, 3, and 4) are in non-conduction, whereas Diodes D3 and D4 engage in conduction. The inductor voltages in this mode are VL1 = -Vo and VL2 = -Vo.

3.3 Mode 3 (Ts < t < 2DTs): IGBTs 2 and 4 transition into conduction, while IGBTs 1 and 3, along with Diodes D3 and D4, remain non-conductive.

3.4 Mode 4 (2DTs < t < 2Ts): All IGBTs remain non-conductive, with Diodes D3 and D4 assuming conduction mode.

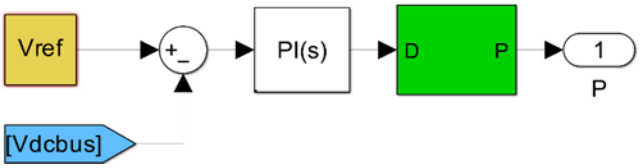

Fig-6: PI controller for High current density converter

The figure 4 shows the PI controller for regulating the DC bus voltage at 245V.

Table -2: Design specifications of High current density DC-DC Converter

S.NO	Parameter	Value
1	C1	1000 µC
2	L1	1 mH
3	L2	1 mH
4	RC1	1000 µC, 1mΩ
5	RC2	1000 µC, 1mΩ
6	L3	1 mH
7	L4	1 mH
8	RC3	1000 µC, 1mΩ
9	Vin	48 V
10	Vout	120 V

4. HIGH-EFFICIENCY BIDIRECTIONAL CONVERTER

The bidirectional converter for Electric Double-Layer Capacitors (EDLCs) is crucial for sophisticated energy modulation during BLDC motor acceleration and deceleration. In acceleration, it precisely transmits stored electrostatic energy to amplify motor performance, while in braking, it efficiently recaptures kinetic energy into the EDLCs, significantly optimizing system energy efficiency.

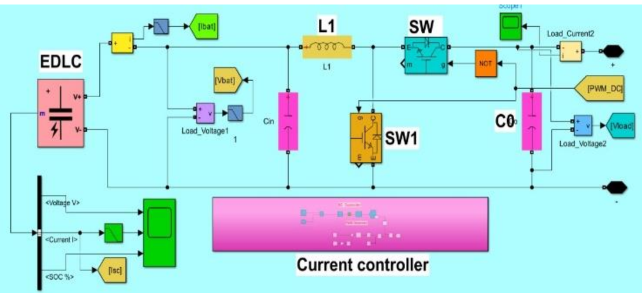

Fig -7: Schematic of the Bidirectional Converter for Regenerative Braking and Charging EDLC's

Table -3: Design specifications of BDLC bank

S.NO	Parameter	Value
1	Rated capacitance	99.5 F
2	DC series resistance	8.9mΩ
3	Rated voltage	72V
4	Number of series capacitors	18
5	Number of Parallel capacitors	1
6	Initial Voltage	72V
7	Operating temperature	25 degrees

Table -4: Design specifications of the Battery system

S.NO	Parameter	Value	
1	Nominal Voltage	48	V
2	Rated Capacity	100	Ah
3	Initial State of charge (SOC)	50	%
4	Battery response time	1	s

Table -5: Design specifications of fuel cell

S.NO	Parameter	Value
1	Model AFC	2.4 KW, 48V
2	Rated Capacity	100 Ah
3	H2, O2, H20	99.95 %, 21%, 1%
4	Nominal supply pressure	Fuel = 1.5 bar, Air = 1 bar

5. DYNAMIC MODELLING OF VEHICLE SYSTEM AND FOC CONTROLLER WITH REGENERATIVE BRAKING

The vehicle model is meticulously constructed within MATLAB Simulink, incorporating an advanced longitudinal driver algorithm. This driver synchronizes with reference velocity profiles derived from Indian drive cycle data, enabling precise, real-time feedback integration with the vehicle dynamics. The transmission system is seamlessly Fig- coupled to a Brushless DC (BLDC) motor, facilitating the efficient transfer of generated torque to propel the motor, ensuring optimal performance and propulsion. The clarke and inverse Clarke transformation is illustrated as,

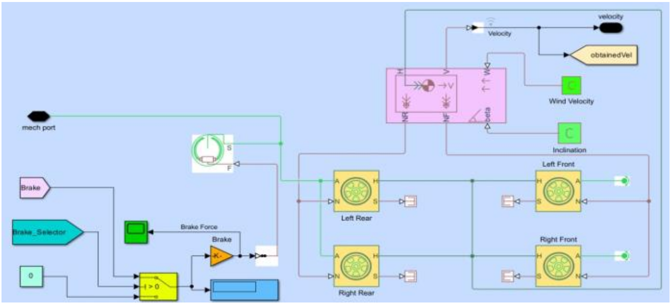

Fig -8 Simulink Model for dynamic vehicle system

$$I\alpha = Ia \quad (1)$$

$$I\beta = [1/(1.732)]*(Ia-Ib) \quad (2)$$

$$Id = I\alpha Cos\,(\theta) + I\beta Sin\,(\theta) \quad (3)$$

$$Iq = -\,[I\alpha Cos\,(\theta) + I\beta Sin\,(\theta)] \quad (4)$$

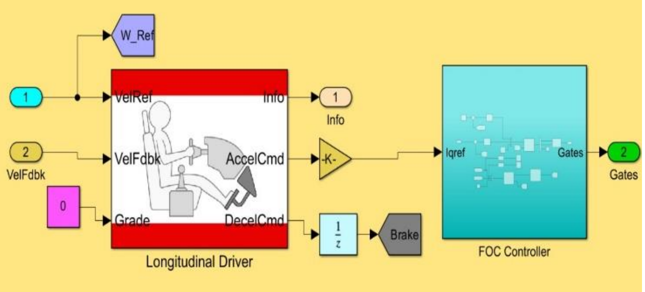

Fig -9: Simulink diagram of Longitudinal driver

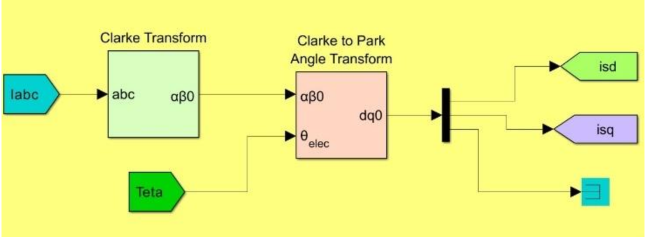

Fig -10: The transformation process of Iabc into the Idq rotating reference frame is delineated comprehensively.

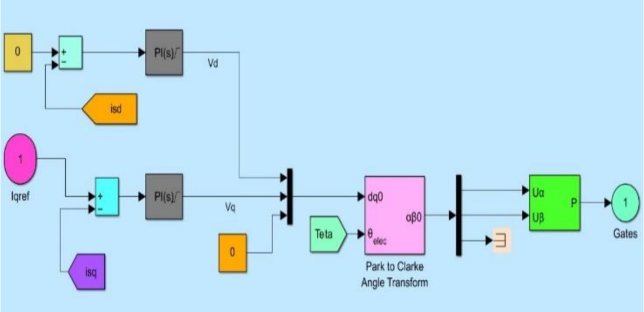

Fig -11: Simulink schematic exemplifying the Field Oriented Controller (FOC) for regulating the BLDC motor

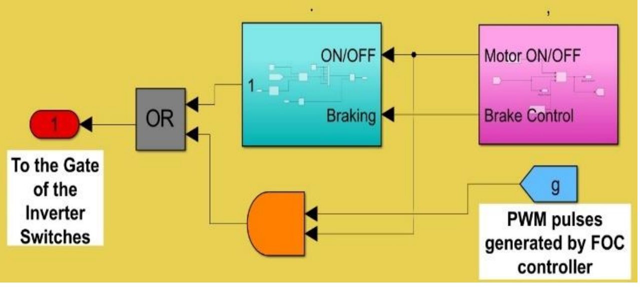

Fig -12: The Simulink diagram of the regenerative braking system for charging the EDLC during braking action.

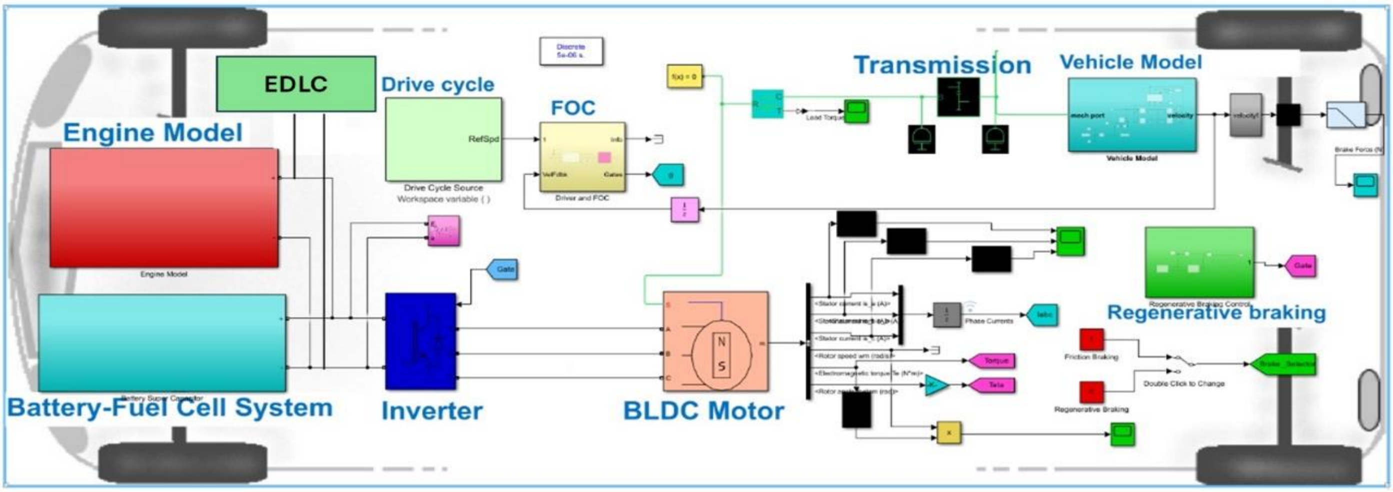

Fig -13: The Simulink architecture of the envisioned system

6. RESULTS AND ANALYSIS

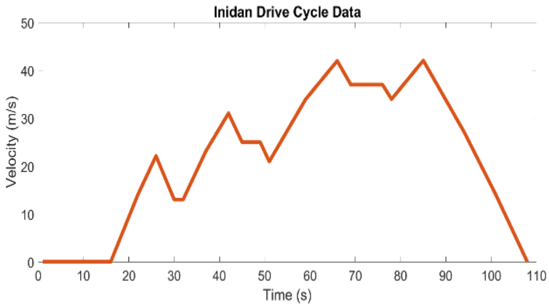

Fig -14: The (Indian drive cycle) IDC spanning for 108s

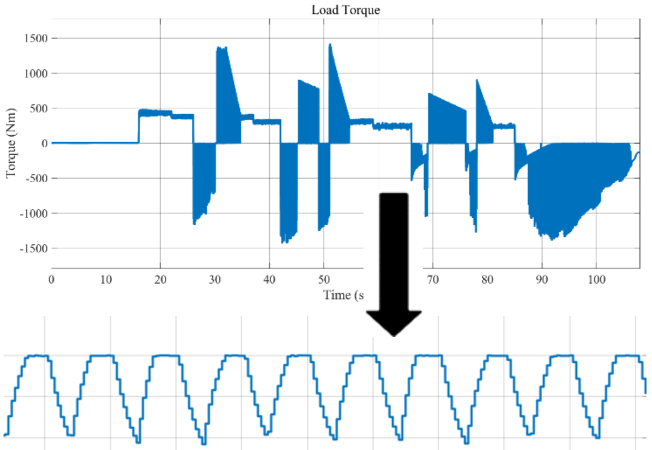

Fig -15: Torque characteristic curve during the drive cycle.

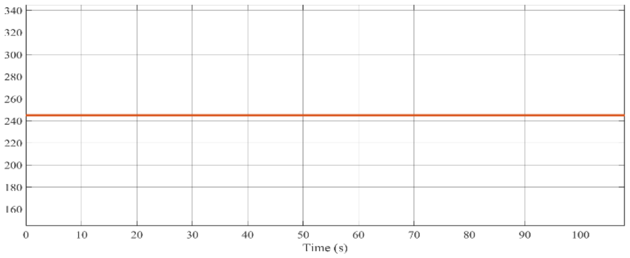

Fig -16: DC bus voltage maintained at 245V

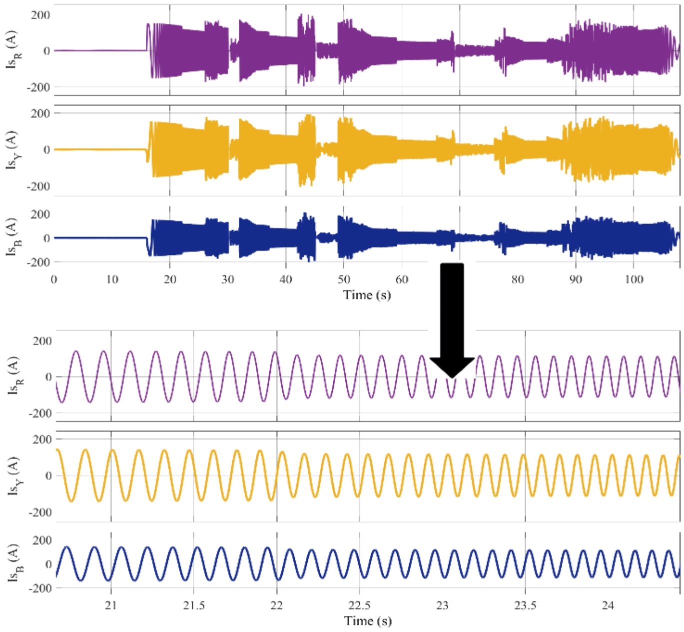

Fig -17: Isa, Isb, Isc stator currents of the BLDC motor

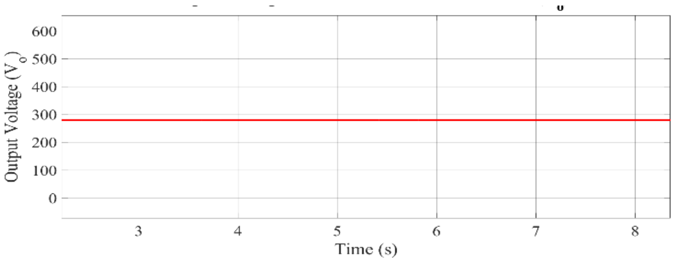

Fig -18: Vo of High current density DC-DC converter

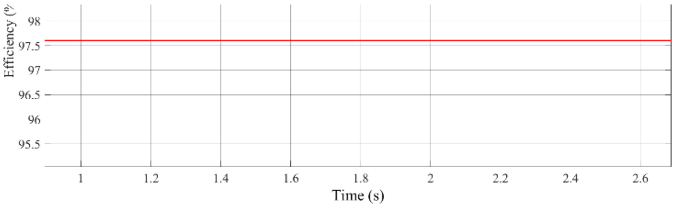

Fig -19: Motoring efficiency of BLDC motor (97.5%)

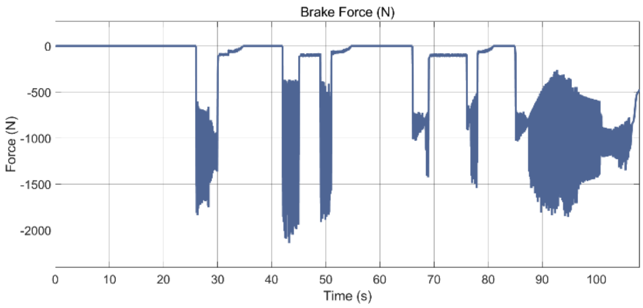

Fig -20: Braking force exerted during the drive cycle

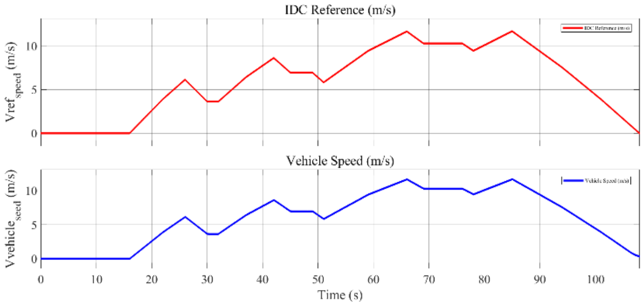

Fig -21: The reference speed and vehicle speed (m/s)

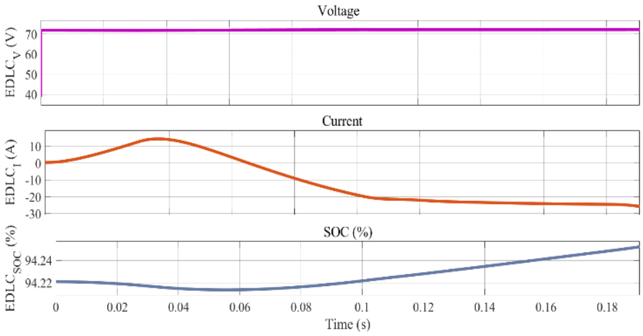

Fig -22: Voltage, current and SOC of the EDLC bank

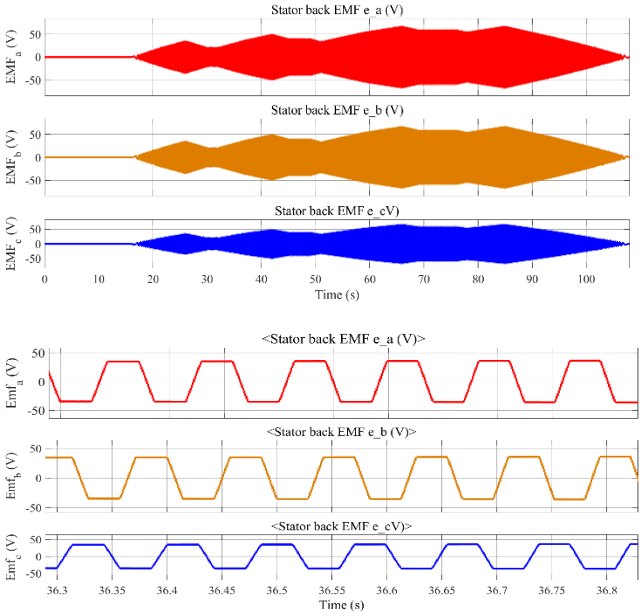

Fig -23: Back emf of the BLDC motor throughout IDC

The DC bus link is maintained at 245V, the stator currents is depicted in figure 17. The motoring efficiency of 97.5% is obtained as depicted in figure 19, the vehicle speed is depicted in figure 21, the back emf in figure 23. During braking action, the EDLC system charges and stores the energy generated during regenerative braking.

7. CONCLUSIONS

HEVs revolutionize electromobility by combining advanced technologies with eco-friendly design, enhancing energy autonomy and reducing fossil fuel use. Leveraging sophisticated converters such as flux additive DC-DC, High current density DC-DC converters and optimization algorithms in maximising the efficiency of the system, the proposed system of HEVs achieve superior performance and sustainability, as demonstrated by MATLAB simulations.

8. REFERENCES

[1] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, “A review on electric vehicles”: Technologies and challenges, Smart Cities, vol. 4, no. 1, pp. 372404, Mar. 2021.

[2] T. Payarou and P. Pillay, "Integrated Multipurpose Power Electronics Interface for Electric Vehicles," *in IEEE Transactions on Transportation Electrification*, vol. 9, no. 2, pp. 2429-2443, June 2023, doi: 10.1109/TTE.2022.3209098.

[3] C. Liu, K. T. Chau, D. Wu and S. Gao, "Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies," in *Proceedings of the IEEE*, vol. 101, no. 11, pp. 2409-2427, Nov. 2013, doi: 10.1109/JPROC.2013.2271951.

[4] D. Wu, D. C. Aliprantis and K. Gkritza, "Electric Energy and Power Consumption by Light-Duty Plug-In Electric Vehicles," *in IEEE Transactions on Power Systems*, vol. 26, no. 2, pp. 738-746, May 2011, doi: 10.1109/TPWRS.2010.2052375.

[5] M. R. Haque, K. M. A. Salam and M. A. Razzak, "A Modified PI-Controller Based High Current Density DC–DC Converter for EV Charging Applications," in IEEE Access, vol. 11, pp. 27246-27266, 2023, doi: 10.1109/ACCESS.2023.3258181.

BIOGRAPHIES

S.G SRIVANI (Senior Member, IEEE) received the ME degree from Bangalore University and Ph. D degree from NITK, Surathkal, is currently the Professor and HOD of EEE, RV College of Engineering, Bengaluru.

V Srinivasulu received the B.E. degree in EEE from Visvesvaraya Technological University, Belagavi, He is currently pursuing his M. Tech in Power Electronics in RV College of Engineering, Bengaluru.