JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Converter Topologies Used in EVs And HEVs

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Abstract: This research paper focuses on the design, development, and simulation of a DC–DC converter using MATLAB/Simulink to analyze its performance and efficiency. Electric and hybrid electric vehicles (EVs and HEVs) have emerged as key technologies for achieving sustainable and energy-efficient transportation. These vehicles rely heavily on efficient and reliable power management systems to regulate the flow of energy between high-voltage traction batteries, electric motors, and low-voltage auxiliary systems. Ensuring seamless power conversion is crucial for maintaining performance, extending driving range, and enhancing system durability. One of the major technical challenges in the design of EVs and HEVs lies in the selection and optimization of suitable power converter topologies. Power converters must achieve high efficiency, compact size, thermal stability, and bidirectional power flow to meet the varying demands of different driving and regenerative braking conditions. The improper choice or design of a converter can lead to significant energy losses, thermal stress, voltage instability, and consequently, reduced system efficiency and shorter battery lifespan. Therefore, the development of optimal converter configurations is essential for improving the overall performance and reliability of electric powertrains. This study focuses on the analysis and comparison of various DC–DC converter topologies commonly employed in electric vehicles, such as buck, boost, buck-boost, SEPIC, CUK, and bidirectional converters. The objective is to identify compact and lightweight designs capable of meeting the high-power density and energy efficiency requirements of modern EVs. Each converter topology is evaluated based on key performance metrics including voltage conversion ratio, efficiency, component count, power density, and thermal characteristics. Through comprehensive comparison and performance evaluation, the study aims to determine the most suitable converter topology that balances efficiency, size, and reliability for electric vehicle applications.

Index Terms: DC–DC converter, MATLAB/Simulink, Switching Devices, Inductor, Capacitor, Electric Vehicles

I. INTRODUCTION:

An electric vehicle (EV) is a type of vehicle that runs on electricity rather than internal combustion. This electricity is usually stored in a battery and supplied to an electric motor, which powers the vehicle's propulsion system. One of the main advantages of EVs is that they produce zero emissions at the point of use, which makes them a cleaner alternative to traditional gasoline-powered vehicles. In addition, the cost of operating an EV is typically lower than that of a gasoline-powered vehicle, as electricity is cheaper than gasoline and EVs require less maintenance. EVs come in a variety of different forms, including cars, buses, trucks, and motorcycles. Some EVs are fully electric, meaning that they can only be powered by electricity, while others are hybrids, which combine an electric motor with a gasoline or diesel engine. Overall, electric vehicles are a promising technology for reducing the environmental impact and dependency on fossil fuels of transportation . In an electric vehicle, power electronic converters play a vital role in managing and controlling the flow of electrical energy between different components such as the battery, motor, and charging system. These converters form the heart of the EV's powertrain, enabling efficient energy conversion and ensuring optimal performance. Various converter topologies including DC-DC converters, DC-AC inverters, and AC-DC rectifiers—are employed depending on the specific subsystem and power requirements. For instance, DC-DC converters regulate the voltage levels between the battery and auxiliary systems, while inverters convert DC power from the battery into AC power to drive the electric motor. The selection and design of appropriate converter topologies are crucial for achieving high efficiency, compact size, thermal management, and overall reliability of electric vehicles.

II. OBJECTIVES

1. Understand and analyze the various types of DC-to-DC & DC-to-AC converters used in electric vehicles
2. Identify compact, lightweight converter design that meet the high-power density needs of EVs.
3. Compare various types of converters according to the result and find out best suitable converter for EV

III. LITERATURE REVIEW:

1. **M. Vairavel, R. Girimurugan, C. Shailaja, et al. "Modeling, validation and simulation of electric vehicles using MATLAB." AIP Conference Proceedings 2452, 030006 (2022), 18th November 2022:** This research paper describes a technique for designing and developing high-performance electric vehicle (EV) powertrains through accurate modeling, simulation, and real-world testing. It emphasizes that precise EV powertrain modeling is vital for effective design and management decisions. Using MATLAB/Simulink, the study models and simulates the EV powertrain, validating results through real vehicle testing on a structural dynamometer. This integrated approach enhances efficiency, reliability, and performance while reducing development costs, offering a practical framework for rapid and accurate EV powertrain evaluation.

2. **Vasupalli Manoj, Ramana Pilla and Srinivasa Rao Sura. "A Comprehensive Analysis of Power Converter Topologies and Control Methods for Extremely Fast Charging of Electric Vehicles." Journal of Physics: Conference Series, 1st September 2023:** This research paper describes the need for advanced, cost-effective, and reliable power electronic converters to address EV battery and charging challenges. It focuses on off-board EV chargers, detailing AC–DC and DC–DC power stages, their topologies, and design considerations for extreme fast-charging (XFC) stations. The study reviews modern converter architectures, control strategies, and emerging multi-port charging systems integrating photovoltaics, energy storage, and the grid. By comparing AC–DC rectifiers, DC–DC converters, and multi-port converters in terms of structure, voltage range, and efficiency, this work guides future research toward optimized EV charging solutions.

3. **Anu Priya, |Dr. S. Senthil Kumar. "Review on Converters used in Electric Vehicle Drive System." International Journal for Modern Trends in Science and Technology, ISSN: 2455-3778 online, 1st September 2023:** This research paper describes the growing adoption of electric vehicles (EVs) driven by their high performance and eco-friendly nature. The efficiency of EVs relies on effective interaction between the energy storage system and propulsion motor. The motor converter, a crucial component, transforms stored electrical energy into mechanical energy for propulsion. This study reviews motor converters used in EV drive systems, including non-isolated DC/DC converters and DC/AC converters for motor operation. Despite their advantages, EV converters face issues such as high component count, current stress, switching losses, slow dynamic response, and computational complexity. The paper analyzes various converter topologies, detailing their configurations, features, operation, and performance trade-offs.

4. **Rejaul Islam, S M Sajjad Hossain Rafin 2 and Osama A. Mohammed. "Comprehensive Review of Power Electronic Converters in Electric Vehicle Applications" Energy Systems Research Laboratory, , 29th December 2022:** This research paper describes the need for high-voltage energy storage, efficient motors, powertrains, and converters in emerging electric vehicle (EV) technology. It reviews various converter topologies, control schemes, reliability, efficiency, and charging systems to support future EV demands. The study helps engineers predict charging durations, energy storage lifespan, and performance using control and machine learning methods. It identifies the Vienna rectifier as the best AC–DC converter, the interleaved DC–DC boost converter for DC–DC conversion, and the third harmonic injected seven-level inverter for DC–AC stages. The paper also discusses wireless power transfer, wide bandgap semiconductors, and multi-level inverter technologies that enhance power density, switching speed, and overall EV efficiency.

I. BASIC CONCEPT OF EV

Fig.No.1 represents the electric vehicle (EV) powertrain system, showing the main components and energy flow. The battery pack serves as the primary energy source, storing electrical energy for propulsion. It can be charged either through AC charging via an on-board charger, which converts AC power from the grid into DC power for the battery, or directly through DC fast charging (DC EVSE), which bypasses the on-board charger. The stored DC power from the battery is fed into the converter and controller unit, which converts it into suitable AC power to drive the electric motor (M). The controller also regulates power flow and manages speed and torque based on driver input. The motor's mechanical output is transmitted to the wheels through a single-ratio transmission, which provides a fixed gear ratio for efficient torque transfer and vehicle movement. Overall, this diagram illustrates how electrical energy from the grid is converted into mechanical motion in an electric vehicle.

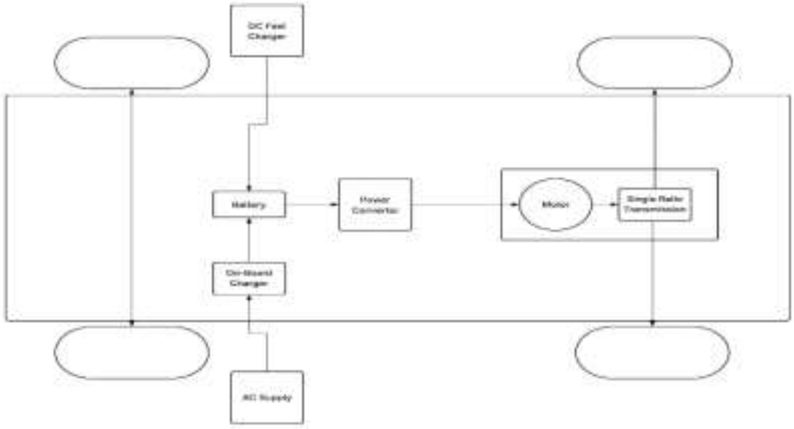

Figure No.1 Basic Block Diagram of EV

II. CLASSIFICATION OF CONVERTER

The Figure No. 2 represents the classification of DC-DC converters into two main categories: isolated and non-isolated converters. Isolated converters use a transformer to provide electrical isolation between the input and output, ensuring safety and allowing voltage step-up or step-down as needed. Examples of isolated converters include Push-Pull, LLC Resonant, and Flyback converters, which are commonly used in high-voltage or safety-critical applications. On the other hand, non-isolated converters do not use a transformer, so the input and output share a common ground. These converters are more compact, efficient, and suitable for low-voltage applications. Examples include Buck, Boost, Buck-Boost, CUK, and SEPIC converters, which are mainly used for voltage regulation in portable and electronic devices.

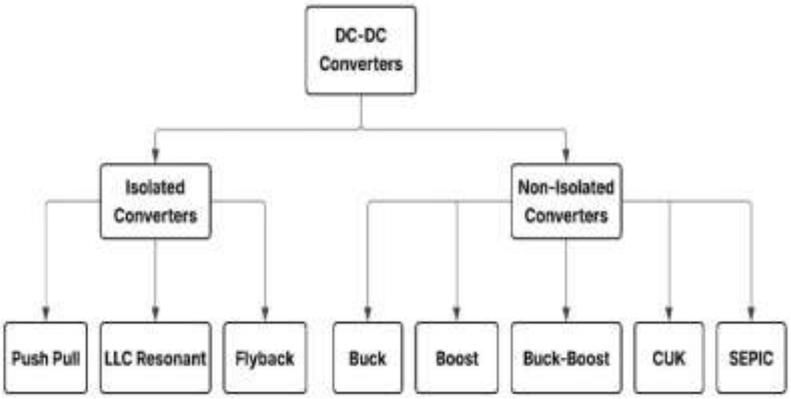

Figure No.2 Classification of DC-DC Converters

III. TYPES OF CONVERTERS

Following types of converters are studied and its simulation work done in MATLAB.

1.Buck-Boost Converter

The Figure No. 3 represents buck-boost converter is a type of dc-dc converter that provides an output voltage either higher or lower than the input voltage. It operates by controlling the duty cycle of a switching device to regulate energy transfer through an inductor. During the on period, energy is stored in the inductor, and during the off period, it is released to the load. The output voltage is inverted in polarity compared to the input. It is widely used in applications like battery charging, solar systems, and portable power devices.

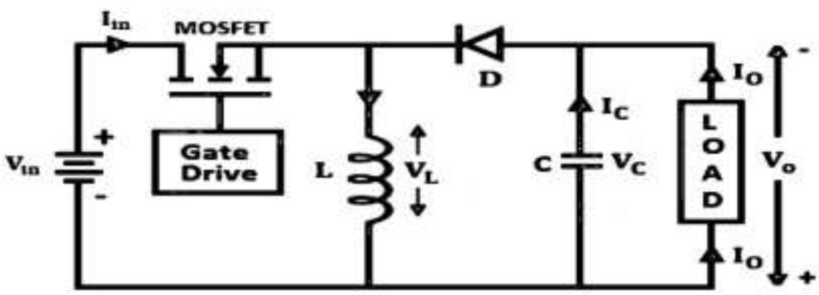

Figure No. 3 Buck-Boost Converter

2.SEPIC Converter

The Figure No.4 represents SEPIC Converter (Single-Ended Primary Inductor Converter) is a DC-DC converter that can step up or step down the input voltage without changing the output polarity. It uses two inductors (or a coupled inductor), a capacitor, a diode, and a switch to transfer energy efficiently. The converter provides a positive output voltage relative to the input ground. It offers low input current ripple and good efficiency, making it suitable for battery-powered and renewable energy applications.

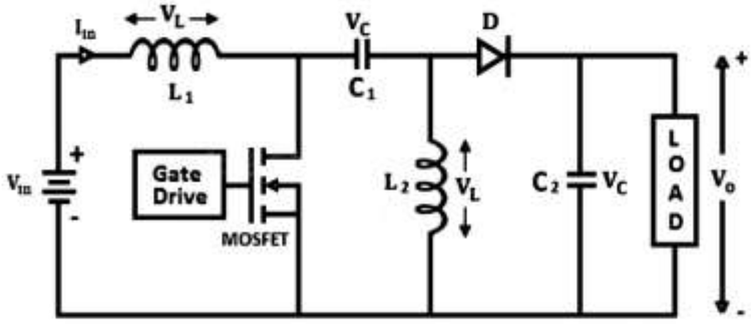

Figure No.4 SEPIC Converter

3.Cuk Converter

The Figure No.5 represents CUK Converter is a DC-DC converter that can step up or step down the input voltage while providing an inverted (negative) output polarity. It uses two inductors and a capacitor for energy transfer, ensuring continuous input and output currents with low ripple. The capacitor acts as an energy-transfer element between input and output. It is widely used in power supply and renewable energy systems where smooth current is required.

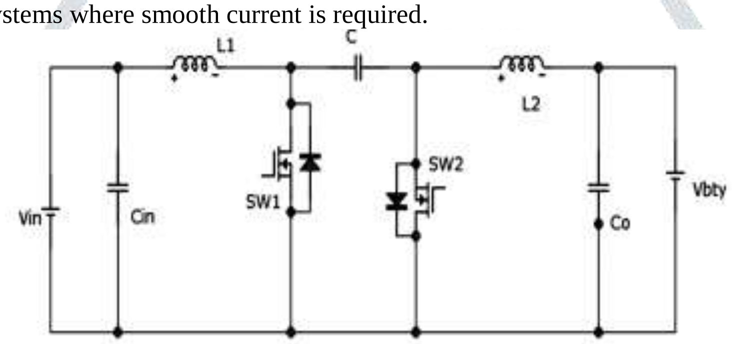

Figure No.5 CUK Converter

4.LLC Resonant Half-Bridge Converter

The Figure No.6 represents LLC Half-Bridge Resonant Converter is a high-efficiency DC-DC converter that uses resonant components (inductor–inductor–capacitor) to achieve soft switching (ZVS/ZCS) and reduce switching losses. It consists of two MOSFETs, a resonant tank (Lr, Lm, Cr), and a high-frequency transformer. The converter regulates output voltage by changing the switching frequency around the resonant point. It is commonly used in server power supplies, battery chargers, and industrial power systems for its high efficiency and low EMI.

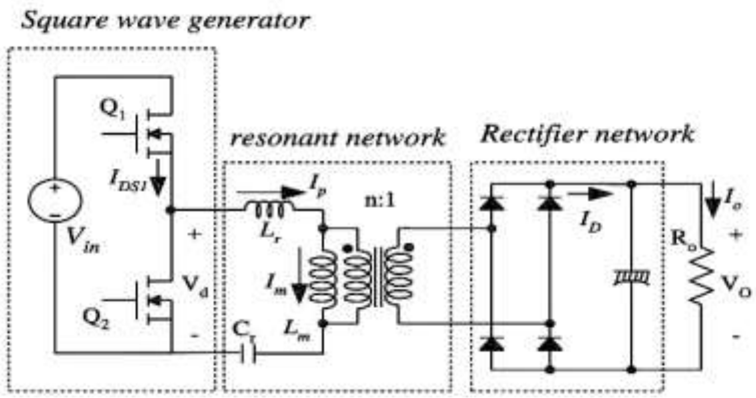

Figure No.6 LLC Half Bridge Resonant Converter

5.Flyback Converter

The Figure No.7 represents Flyback Converter is an isolated DC-DC converter that can step up or step- down voltage using a transformer for energy storage and isolation. It operates by storing energy in the transformer core when the switch is ON and transferring it to the output when the switch is OFF. The circuit uses a switch, diode, transformer, and output capacitor. It is widely used in low-power applications, chargers, and standby power supplies due to its simple design.

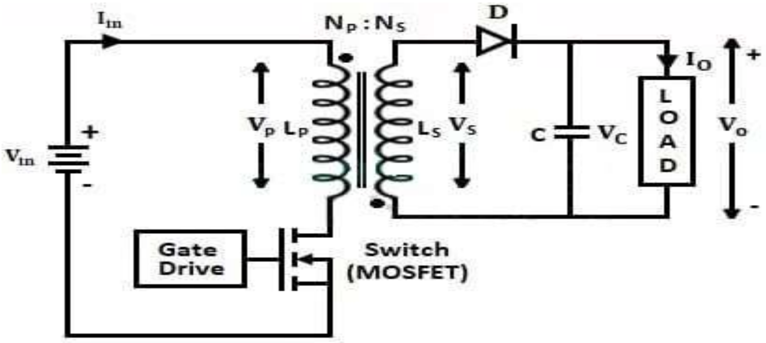

Figure No.7 Flyback Converter

IV. SIMULATION OF FLYBACK CONVERTER

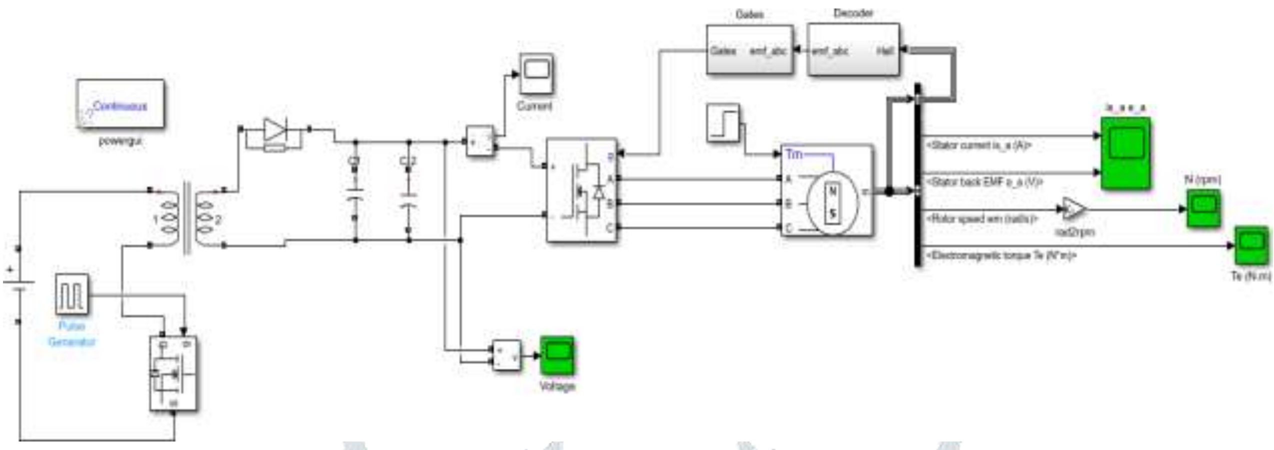

Figure No. 8 represent the simulation diagram of flyback converter

Procedure of Design Flyback Converter MATLAB

The Following are the procedure are followed for the simulation of flyback converter

1.Open the Blank model in MATLAB/Simulink.

2.Collect all the required components – DC voltage source, MOSFET switch, transformer, diode, filter capacitors (C1, C2), resistive load, current and voltage measurement blocks, pulse generator, powergui block, and BLDC motor subsystem.

3. Connect all the bloks as per the circuit diagram shown in Figure No. 8

3.Set the powergui block to Continuous mode for smooth simulation.

4.Select a suitable solver and adjust the step size for better accuracy.

5.Apply the required DC input voltage to the converter's input source.

6.Configure pulse generator to provide the switching signal to the MOSFET gate with the paper frequency and duty cycle.

7.Connect the primary winding of the transformer to the MOSEFT switch and the secondary winding to the rectifier diode followed by the filter capacitors and load.

8. Link the output of the converter to the BLDC motor section, which includes Gate control, Decoder, EMF sensing, and Hall sensors for feedback control.

9 Use the measurement blocks to record and display output voltage, current, motor speed (rpm), torque (Te), and stator current on the Scope.

10. Set the simulation time (e.g., *0.1 s*) and verify all connections carefully.

11.The **Flyback Converter** is an isolated DC-DC converter that can **step up or step down** voltage using a **transformer** for energy storage and isolation. It operates by storing energy in the transformer core when the switch is ON and transferring it to the output when the switch is OFF. The circuit uses a **switch, diode, transformer, and output capacitor**. It is widely used in **low-power applications, chargers, and standby power supplies** due to its **simple design and cost-effectiveness**.

12.Click run to start the simulation and observe waveforms of output voltage(Vo), current, rotor speed (N), and electromagnetic torque (Te) on the scpoe.

Flyback Converter Output Waveforms

The first two graphs show the electrical characteristics of the flyback converter itself.
The waveform below, labeled "Voltage Measurement," depicts the output voltage over a time span of 0 to 0.5 seconds.
0 to 0.1 seconds: In Figure No.9 the voltage rises rapidly from zero. This is the startup phase of the converter as it charges the output capacitor and reaches its target regulated voltage. There appears to be a small overshoot before it settles.
0.1 to 0.5 seconds: The voltage stabilizes around 485V. The curve remains relatively flat with only a slight ripple, indicating the converter is successfully regulating the output voltage under a steady load.

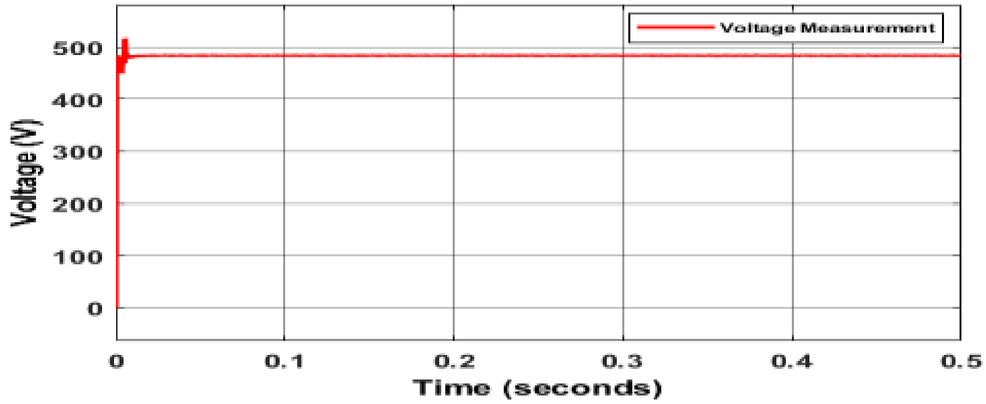

Figure No. 9 Voltage Wave Form of Flyback Converter

The below Figure No.10, labeled "Current Measurement," shows the current pulses over a shorter time span of 0 to 0.1 seconds.
0 to 0.02 seconds: The current exhibits large, high-frequency pulses that are characteristic of the converter's switching action during the initial charging and startup phase.
0.02 to 0.1 seconds: The pulses become smaller in magnitude and more stable in their frequency and shape, indicating that the converter has reached a steady-state operation. The waveform shows the converter operating in discontinuous conduction mode (DCM), where the current falls to zero between switching cycles.

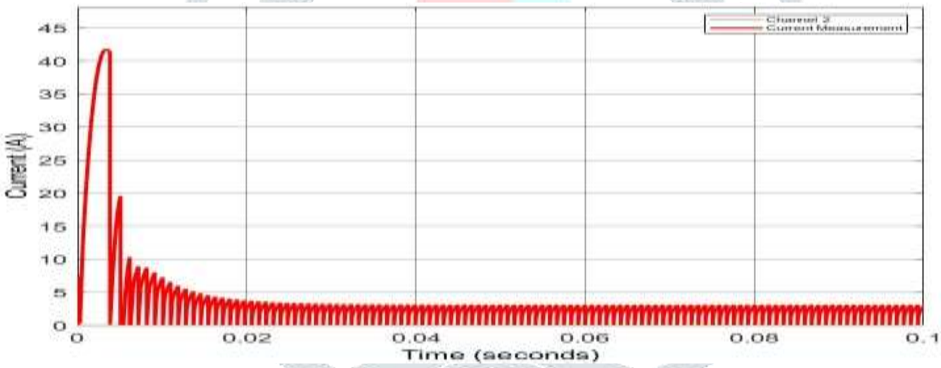

Figure No. 10 Current Wave Form of Flyback Converter

2. Motor Drive Waveforms:
The remaining graphs show the response of the motor being driven by the flyback converter's output.
Figure No.11 shows the motor's speed in RPM over a period of 0 to 0.5 seconds.
0 to 0.2 seconds: In Figure 5.27he speed of the motor increases from 0 RPM, indicating the acceleration phase.
0.2 to 0.5 seconds: The speed stabilizes at a constant value of approximately 3000 RPM, signifying that the motor has reached its steady-state operating speed.

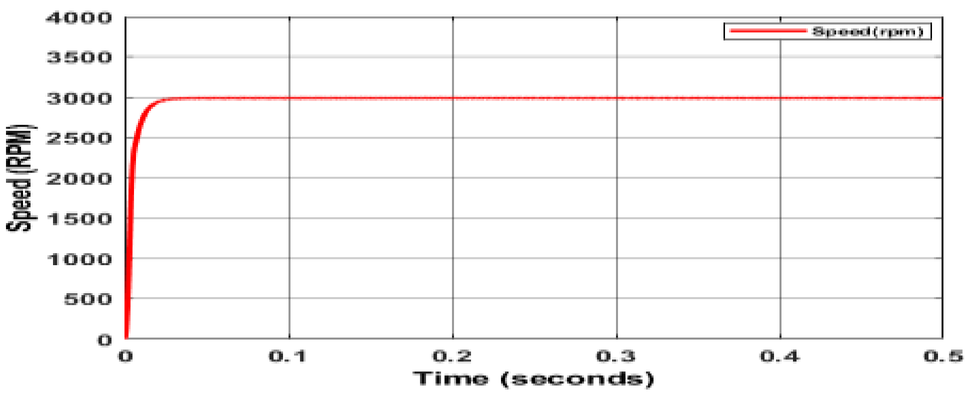

Figure No. 11 Speed (Rpm) Wave Form of Flyback Converter

Figure No.12 shows the electromagnetic torque of the motor over the same 0 to 0.5 second period.
0 to 0.05 seconds: The torque is high and then rapidly decreases. This high torque is required to accelerate the motor from a standstill.
0.05 to 0.5 seconds: The torque settles to a lower, constant value. This represents the steady-state torque needed to overcome mechanical friction and other loads to maintain the motor's constant speed of 3000 RPM.

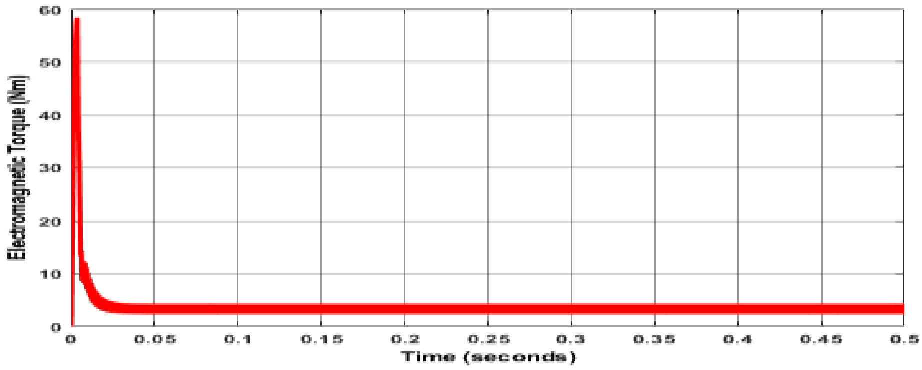

Figure No. 12 Torque Wave Form of Flyback Converter

Figure No.13 shows the back-EMF (electromotive force) generated in the motor's stator windings over time.
0 to 0.5 seconds: The waveform shows a series of repeating pulses. The frequency and magnitude of these pulses increase as the motor accelerates and then become constant as the motor reaches its steady speed. The constant frequency and amplitude from approximately 0.2 seconds onward correspond to the motor's stable 3000 RPM speed.

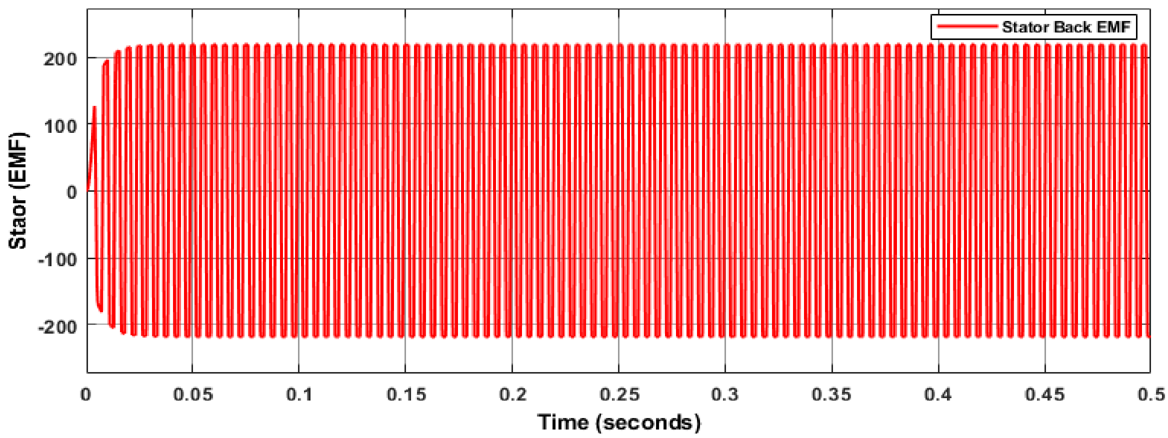

Figure No. 13 Stator (EMF) Wave Form of Flyback Converter

Figure No. 14 shows the current flowing through the motor's stator over a short time of 0 to 0.1 seconds.
0 to 0.02 seconds: Similar to the converter current, the stator current has large initial pulses during the startup and acceleration phase of the motor.
0.02 to 0.1 seconds: The current pulses become more consistent in both amplitude and frequency, indicating that the motor is operating more smoothly and approaching its steady-state speed.

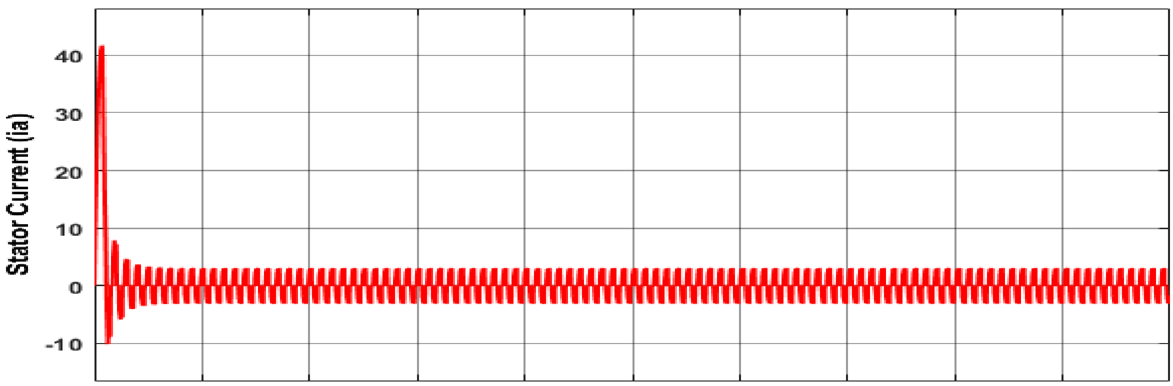

Figure No. 14 Stator Current (Ia) Wave Form of Flyback Converter

V. RESULT

The Table No.1compares the performance of different DC–DC converter topologies used in electric vehicles, including Buck-Boost, SEPIC, CUK, LLC Resonant, and Flyback converters. Each converter affects key performance parameters such as boosted voltage, current, electromagnetic torque, rotor speed and settling time of the motor. The boosted voltage indicates how much the converter increases the battery voltage to drive the motor efficiently. The current represents the electrical load drawn by the converter, while the electromagnetic torque shows the motor's torque-producing capability. The rotor speed corresponds to how fast the motor rotates, and the settling time measures how quickly the motor speed stabilizes after a transient disturbance lower values imply faster dynamic response.

Table no.1 Parameters of converters with motor

Types of Converters	Boosted Voltage (v)	Current I (Amp)	Electro-magnetic Torque (Nm)	Rotor Speed (rpm)	Settling time Ts (Sec) w.r.t. Speed
Buck-Boost Converter	511	3.4	4.6	3002	0.085
SEPIC Converter	485	3.01	4.03	3006	0.14
CUK Converter	495	2.01	6.1	2911	0.05
LLC Resonant Converter	490	2.16	2.88	3026	0.045
Flyback Converter	496	2.85	3.83	3072	0.04

The Table no.2 provides a comparative analysis of five common DC–DC converters used in electric vehicle (EV) systems, evaluating their voltage efficiency, current efficiency, torque capability, speed response, and overall performance characteristics. The Buck–Boost converter demonstrates excellent voltage and current efficiency, making it suitable for high-power applications with moderate torque and fast speed response. The SEPIC converter offers stable operation and average output performance but has lower torque and moderate current efficiency, resulting in a slower overall response. The Cuk converter stands out with the highest torque performance, making it ideal for applications requiring strong motor drive capability, although its current efficiency is lower. The LLC resonant converter provides extremely fast response and high-speed capability due to its soft-switching characteristics, but it delivers comparatively lower torque. The Flyback converter offers the fastest dynamic response and balanced performance, though its torque capability is limited, making it more suitable for low- to medium-power EV subsystems. Overall, the table highlights how each converter has specific strengths and limitations, and selecting the appropriate converter depends on the desired balance between torque, efficiency, response time, and application requirements in EV power systems.

Table no. 2 Performance of different converters with motor

Converter	Voltage	Current Efficiency	Torque	Speed	Remarks
Buck-Boost Converter	100%	100%	75%	98%	High Power, Moderate Response
SEPIC Converter	95%	89%	66%	98%	Slower Response, Average Output
CUK Converter	97%	59%	100%	95%	Best Torque, High Efficiency
LLC-Resonant Converter	96%	64%	67%	99%	Fast Response, Low Torque
Flyback Converter	97%	84%	63%	100%	Fastest response, Balanced performance

VI. CONCLUSION

- The CUK converter achieves torque performance with lowest current draw, indicating the best torque efficiency.
- The Flyback converter offers fastest transient response and maximum speed, making it ideal for quick dynamic control.
- The LLC Resonant converter also provides good dynamic behaviour with short settling time but lower torque output.
- The Buck-Boost converter handles highest voltage and current, suitable for high power requirements, though its response time is moderate.
- The SEPIC converter performs adequately but has the slowest response making it less favourable for applications needing fast control.
- In this research paper, CUK is best for torque and efficiency, while Flyback is best for fast response and stable high-speed operation.

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