



## PERFORMANCE IMPROVEMENT OF A BOOST CONVERTER DRIVING A SEPARATELY EXCITED DC MOTOR USING INDUCTOR-CAPACITOR (LC)

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### ARTICLE INFORMATION ABSTRACT

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The increasing use of boost converter circuits for driving DC motors is attributed to their ability to provide extensive adjustable speed control, frequent starting, precise speed regulation, braking, and reversing capabilities. However, the presence of harmonic content poses a significant challenge for these converters. This study investigates the performance enhancements achieved through the integration of an Inductor-Capacitor (LC) filter in a boost converter circuit driving a separately excited DC motor. Simulation results demonstrate significant improvements in both converter and motor performance with the LC filter. The average output voltage and current of the converter increase from 122.61 V and 31.24 A to 129.30 V and 34.39 A, respectively, indicating effective ripple mitigation. Additionally, the motor speed rises from 1103 rpm to 1205 rpm, with corresponding improvements in efficiency for both the converter (from 81.21% to 94.18%) and the motor (from 68.32% to 85.13%) with the LC filter. These improvements highlight the critical role of the LC filter in reducing losses, enhancing motor performance, and achieving overall system efficiency gains. These findings highlight the significance of innovative filtering techniques in optimizing power electronics systems and motor control applications.

### 1.0 Introduction

Direct current (DC) power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, as well as DC Motor drives (Forouzesh *et al.*, 2017). Separately excited Direct Current (DC) motor is widely used in many industrial sectors. During the operation of the DC motor, the load torque and the voltage of the network can cause a destabilization of the actual speed and actual current (Nagarajan *et al.*, 2016). Thus, the need to regulate the speed and current of the DC motor is a crucial research problem. There are several ways to regulate and improve the performance of Separately Excited DC motors, however the most common is the use of Boost Converter circuit. One way to improve the performance of the DC Motor fed by the boost converter is the use of an efficient filtering circuit which is the direction of this study.

There are several works and investigations that proposed their techniques on filter, boost converter and separately excited DC motor speed control, among them are the following. Hamida *et al.* (2019) used proportional integral (PI) and petri net controller to control the speed of DC motor, the later controller ensures armature current was maintained and regulated and the former maintained the capacitor voltage of the multi-cell converter to its reference voltage.

Sahana *et al.* (2016) designed and implemented separately excited DC motor speed control mechanism using chopper circuit using two different control loop thus current controller and speed controller. Nagarajan *et al.* (2016) proposed a speed control strategy of separately excited DC motor fed by Chopper circuit, the circuit offers variable voltage to the armature of the motor to achieved desired speed using PI controller. Jaafer and Mahdi (2013) enhanced the performance and controlled the speed of separately excited DC motor using an Insulated Gate Bipolar Transistor (IGBT-based chopper) by varying the armature voltage and field flux thus, the speed was control within the desired limit.

A nonlinear autoregressive moving average controller for speed control of Sinkers Electrical Discharge Machining (SEDM) was proposed and its performance was compared with that of the traditional conventional controller by George (2008). Furthermore, the chopper integrated with PI controller with two control loop was implemented for efficiency improvement and precise speed control (Uma and Babu, 2015). Boost chopper with high conversion efficiency, with low weight and volume was designed and evaluated for the HFC hybrid railroad system by Youn *et al.* (2020). Moreover, Zhang *et al.* (2023) proposed high gain DC-DC converter for improving the performance of the converter, the proposed converter supplies power to the load by connecting capacitors with the input source in series in switch-on state while the input source charges the capacitor through series connection with the inductor in switch-off state. Nayak and Shivarudraswamy (2020) proposed a Photovoltaic (PV) as the source of Boost converter feeding Brushless Direct Current (BLDC) motor for mixer grinder was proposed and implemented, the absence of brushes reduces noise and the efficiency was improved. Additionally, Usman *et al.* (2024) designed an effective LC filter for optimal speed control of DC motor. Moreover, Al-Maliki and Iqbal (2018) proposed a PID controller for efficient and precise speed control of DC motor with less noise, overshoot and improved steady-state error. On the other hand, converter with bidirectional power flow capabilities was designed with a DC link of the motor drive system, such that during braking, the energy is recovered and stored in an accumulator which is used in Battery-fed electric vehicles (BFEVs) (Pany *et al.*, 2011). The control of separately excited DC motor was proposed using fuzzy neural model reference controller and thus solved the drawback of conventional controller (Ahmed *et al.*, 2020). Other studies by Dhanke and Wanjari (2017), Usman *et al.* (2024) focused on design and analysis of a DC motor drive under different conditions of torque as applied in hybrid electric vehicles (HEVs) with complex control system. A passive filter integrated in a converter was designed for mitigating harmonic with a special provision of power capacitor bank for compensating the voltage drop was investigated in Park *et al.* (2021), Deshi *et al.* (2021), and Prasad *et al.* (2023).

The integration of an LC filter into the boost converter circuit for driving DC motors represents a significant contribution to the field of power electronics and motor control. The study demonstrates the effectiveness of the LC filter in mitigating ripple in both the converter's output voltage and current, addressing a key challenge faced by boost converters. This finding is particularly novel as it provides a practical solution to the harmonic content issue, allowing for smoother and more stable power delivery to the motor, which is essential for optimal performance in various applications. Additionally, the study showcases notable improvements in both the efficiency of the boost converter and the separately excited DC motor with the incorporation of the LC filter. The increase in efficiency highlights the practical significance of the study's findings, as it demonstrates the potential for significant energy savings and performance enhancements in real-world applications.

## 2. Materials and Methods

In this study, MATLAB/Simulink was utilized to design and simulate the boost converter-based LC filter model. Specifically, MATLAB was used to develop the mathematical model of the boost converter circuit with the LC filter incorporated. Simulink, an extension of MATLAB, facilitated the construction of the simulation model by visually representing the boost

converter circuit and its components. Parameters such as the input DC voltage, duty ratio, and switching frequency were defined within the simulation environment. MATLAB/Simulink then allowed for the execution of simulations to analyze the behavior of the boost converter system under various operating conditions. Through this approach, the performance of the proposed methodology, including its ability to reduce harmonic content and improve motor response, was evaluated and validated. The procedures followed are;

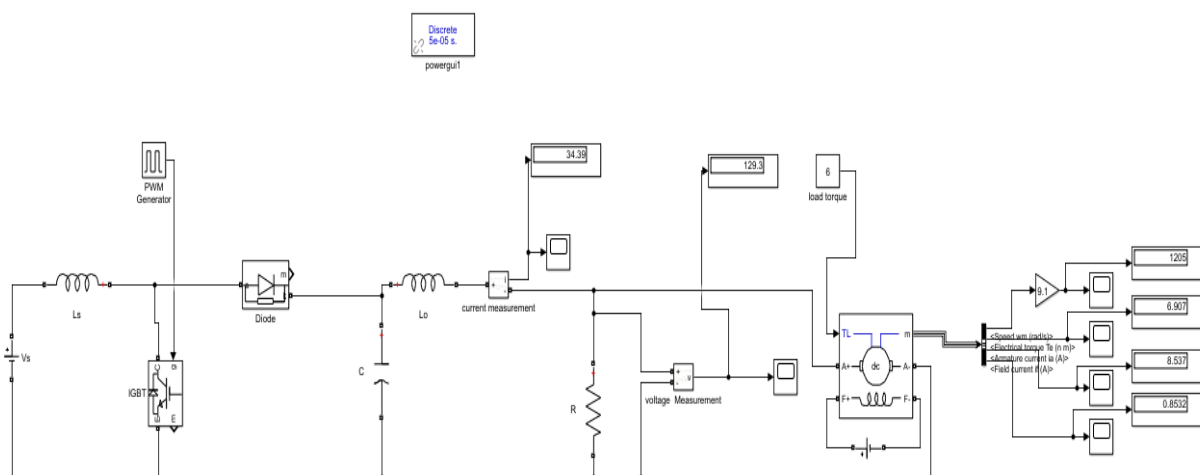
- Modelling of boost converter circuit
- Modelling of LC filter circuit
- Modelling of separately excited DC motor
- Integrating the models together
- Simulation of the complete model
- Efficiency evaluation of the DC motor

## 2.1 Design of the boost converter (with LC filter) that drives separately excited DC motor

The built boost converter circuit with the LC filter is combined with the DC motor model such that the output of the converter circuit serves as the DC motor's input. The complete circuit was designed and simulated using MATLAB (Simulink block). The converter circuit serves as the driver of the DC motor as shown in Figure 1.

## 2.2 Modeling of boost converter

The boost converter also known as step up choppers are the type of chopper circuits that provide output voltage higher than the supplied input voltage such that a fixed DC input is converted in to adjustable DC voltage. As shown in Figure 1, the circuit consist of the arrangement of inductor L in series with source voltage and a switch (usually insulated junction bipolar transistor IJBT) connected in parallel which is controlled (ON-OFF) using pulse width modulation PWM. When the chopper switch (IJBT) is triggered by PWM setting the circuit in ON state as shown in Figure 1, then the DC input current begins to flow through the inductor within the closed path of the circuit.



**Figure 1.** Design of boost converter with LC filter driven separately excited DC motor

$$L = \frac{V_s \times D}{f_s \times \Delta I_O} \quad (1)$$

$$C = \frac{I_o \times D}{f_s \times \Delta V_O} \quad (2)$$

Where

D = duty ratio, L = inductor, C = capacitor,  $f_s$  = switching frequency,  $\Delta I$  is the ripple current which must not exceed 20% to 30% of the average output current, ripple voltage  $\Delta V_o$  must not exceed 20% to 40% of average output volt

Equations 1 and 2 are employed for the modeling and sizing of the inductor and capacitor, in boost converter design respectively.

Additionally, at the instant when the PWM sets the IGBT switch OFF as shown in Figure 1, then the part of the circuit which current was flowing earlier will no longer be active, however as the inductor stores the energy in the form of magnetic field and the current through it will not die out instantly. Also, as we know according to Lenz law, a reverse current will be induced that oppose the cause producing it and due to the induced current, the polarity of the inductor is reversed. This reverse polarity of inductor forward biased the diode D present in the circuit, this provides the path for the current through the diode that flows through the LC filter and finally feeds the DC motor.

$$V_{out} = \frac{V_{in}}{1 - D} \quad (3)$$

Where  $V_{out}$  is the output voltage of the converter,  $V_{in}$  is the voltage input to the converter while D is the duty cycle with value ranging (0 to 1), as such output voltage becomes higher than input as Equation 3 evidenced. However, the output voltage is the summation of the inductor voltage and input voltage resulting to increased voltage output as presented in Equation 3.

### 2.3 Modeling of efficient Inductor-Capacitor (LC) filter

The output voltage and current of boost converter contained harmonics content which result to reduced efficiency. LC Filter is used here to reduce the harmonic distortions to near zero. Equation 4 is used for calculating the impedance of an inductor while Equation 5 is used for calculating the impedance of a capacitor. These equations are fundamental in analyzing and designing filter circuit, particularly in determining how inductors and capacitors react to different frequencies.

$$Z_L = j\omega L \quad (4)$$

$$Z_C = \frac{1}{j\omega C} \quad (5)$$

Where

$Z_L$  = Impedance of the inductor

$Z_c$  = Impedance of the capacitor

L = Inductance of the inductor

C = Capacitance of the capacitor

$\omega$  = Angular frequency (2pi times frequency in Herz)

j = imaginary unit

To find the cut-off frequency  $f_c$  of the filter, where the filter starts to attenuate the higher frequency, this occurs when the reactance of inductor and capacitor are equal in magnitude but opposite in sign. Equating equation (4) and (5)

$$Z_L = Z_C = j\omega_c L = \frac{-1}{j\omega_c C} \quad (6)$$

$$\omega_c = 2\pi f_c \quad (7)$$

Substituting equation (6) in (7) and solving the equations yield

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

Where

$f_c$  = Cut-off frequency in Herz, which is also referred to as switching frequency  $f_s$

Equation 6 equates the impedances of the inductor and capacitor, while equation 7 defines the angular cutoff frequency. Substituting equation 6 into Equation 7 and solving yields the cutoff frequency Equation 8.

$f_s$  = Switching Frequency, the choice of switching frequency is crucial as it affects the efficiency, switching losses, and size of the filtering components. A higher switching frequency allows for smoother waveform transitions, reducing audible noise and improving efficiency. However, excessively high frequencies can lead to increased switching losses and higher component costs. Switching frequency of 50kHz strikes a balance between efficiency and cost-effectiveness, ensuring smooth operation while minimizing losses and component size.

The value of the filter parameter can be obtained using the equations (1), (3), (4). As shown in equation (4), frequency is inversely proportional to the square root of inductor and capacitor, however, inductor L and capacitor C depend on the converter output voltage and current. The LC filter output feeds separately excited DC motor which utilize the electrical energy input and produce rotational speed as shown in figure 1.

$$\omega_m = \frac{1}{K} \left( \frac{V}{1-D} - I_a R_a \right) \quad (9)$$

Equation (9) presents the speed of separately excited DC motor as a function of voltage output of the converter, armature current and voltage and duty cycle. The efficiency of the motor is significantly improved when LC filter is incorporated in the circuit.

## 2.4 Performance Evaluation

For evaluating the performance of a chopper circuit, Equation 10 is used to determine the efficiency of the boost converter, while Equation 11 is used for the efficiency of a separately excited DC motor. Equations 12 and 13 are employed to determine the input and output power of the motor, respectively.

Boost converter efficiency

$$\begin{aligned} \eta &= \frac{\text{Power output}}{\text{Power input}} = \frac{V_o I_o (1-D)}{V_{in} I_o} \\ &= \frac{V_o}{V_{in}} (1-D) \end{aligned} \quad (10)$$

Separately excited DC motor efficiency

$$\gamma = \frac{\text{Power output}}{\text{power input}} \quad (11)$$

$$\text{Power input} = V_o \times I_o \quad (12)$$

$$\text{Power output} = T_L \times \omega_m \quad (13)$$

Where  $V_o$ = Average output voltage of the converter,  $I_o$ = Average output current of the converter,  $T_L$ = Load torque of the motor,  $W_m$ = speed of the motor in revolution per minute (rpm),  $D$ = duty ratio,  $V_{in}$ = voltage input,  $V_{out}$ = voltage output of the converter,  $L$ = inductor,  $C$ = capacitor,  $F$ = frequency,  $W_m$ = speed of the motor in rpm,  $I_a$ = armature current,  $R_a$ = armature resistance,  $P_{in}$ = power input to the DC motor,  $P_{out}$ = output power of the motor,  $V_{trans}$ = transistor voltage,  $V_D$ = diode voltage,  $\Delta I$  is the ripple current which must not exceed 20% to 30% of the average output current ( $I_o$ ), ripple voltage  $\Delta V_o$  must not exceed 20% to 40% of average output voltage.

### 3. Result and Discussion

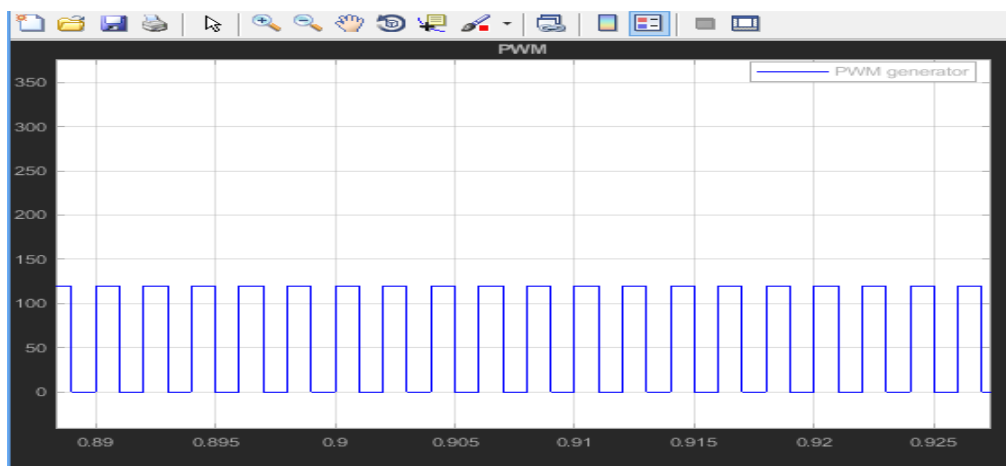
In this study, various input parameters are specified to optimize the system's performance. These parameters include input voltage, source inductance, field voltage, load torque, inductance of the filter, capacitance of the filter, resistance, switching frequency, and duty cycle. The detailed input specification data are presented in Table I.

**Table I:** Input parameter specification

Input parameter	Symbol	Specification
Input Voltage (V)	$V_{in}$	120V
Source inductance (H)	$L$	1mH
Field voltage (V)	$V_f$	120V
Load torque (Nm <sup>2</sup> )	$T_L$	6Nm <sup>2</sup>
Inductance of the filter	$L_o$	0.5mH
Capacitance of the filter	$C$	1uF
Resistance (ohms)	$R$	5ohms
Switching frequency (Hz)	$f_s$	50KHz
Duty cycle (%)	$D$	50%

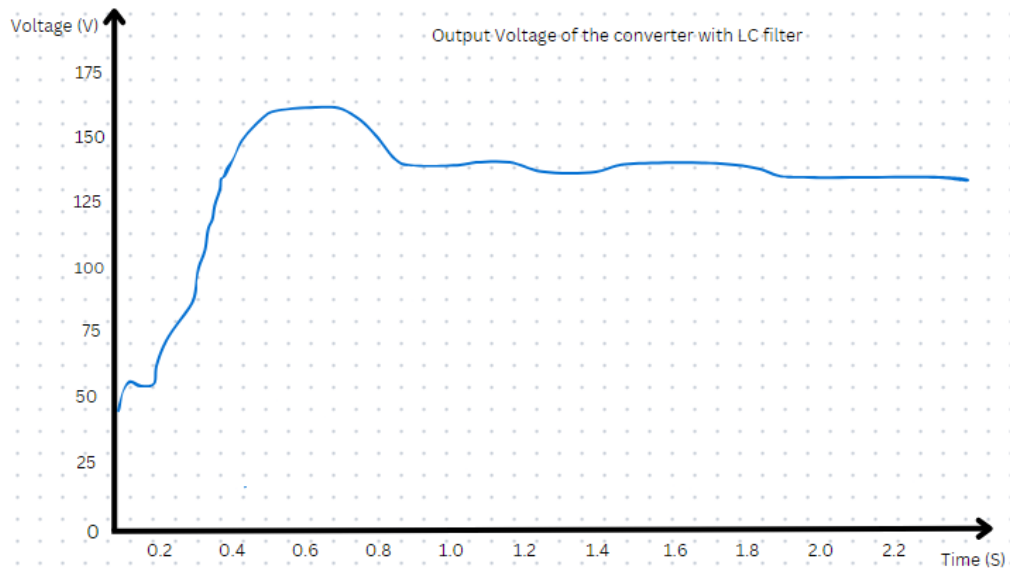
#### 3.1 Modeling and Simulation

A simulation model of a chopper circuit with an innovative LC filter driving a separately excited DC motor was developed using the MATLAB/Simulink package, resulting in significantly enhanced efficiency. The chopper circuit is supplied with a voltage, but its operation relies heavily on the switching of an Insulated Gate Bipolar Transistor (IGBT), achieved through Pulse Width Modulation (PWM) technique. The PWM generator produces pulses that switch the IGBT ON and OFF. Specifically, a PWM signal is generated using the square function in MATLAB/SIMULINK, representing the ON-OFF states of the switch, as illustrated in Figure 2. The Boost Converter Simulation Function then calculates the input and output voltages and currents over time based on this PWM signal. In this study, a duty cycle of 50% and a frequency of 50 kHz are utilized for PWM signal generation, ensuring optimal performance of the chopper circuit.



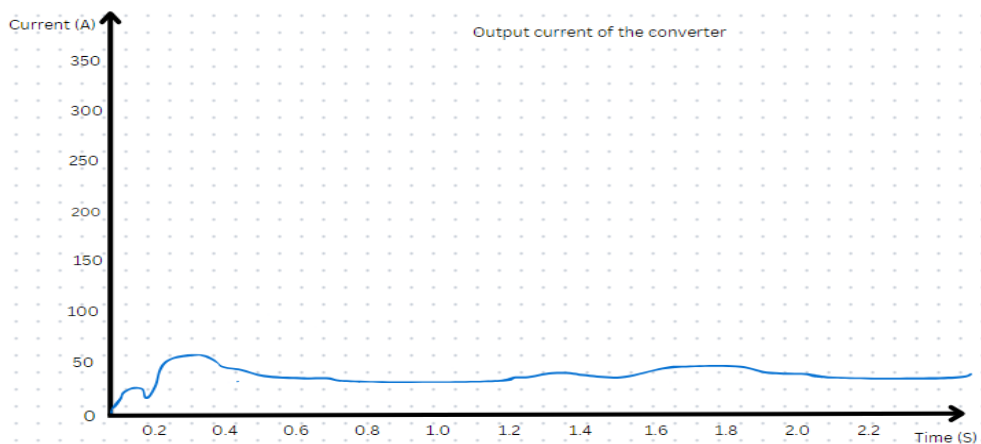
**Figure 2.** Pulse width modulation (PWM)

Figure 3 depicts the simulated output voltage of a chopper circuit equipped with an LC filter driving a separately excited DC motor, as analyzed using MATLAB/Simulink. The average output voltage observed in the Simulink output block is recorded at 129.3 V, demonstrating the effectiveness of the LC filter in smoothing out voltage fluctuations. The Simulink scope graphically represents the voltage response, highlighting minimal ripple, which is a clear indication of the LC filter's ability to stabilize the output voltage. Despite aiming for a target output of 130 V, achieving 129.3 V falls within an acceptable tolerance range, showcasing the robust performance and precise control achieved through this simulation. Comparatively, the chopper circuit without the LC filter yielded an average output voltage of 122.61 V, underscoring the significant improvement achieved by integrating the LC filter in terms of voltage stability and overall system performance.



**Figure 3.** Chopper Circuit Output Voltage with LC filter driven separately excited DC Motor

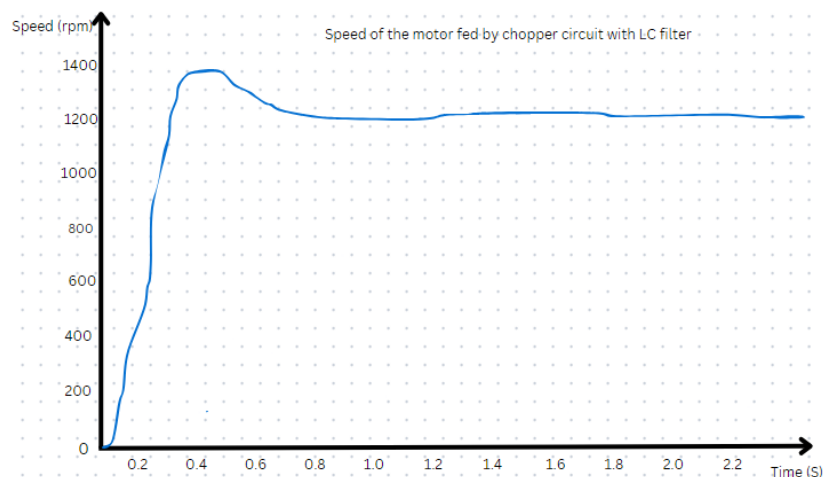
Figure 4 shows the output current of a chopper circuit with an LC filter, simulated using MATLAB/Simulink. The output current is measured at 35.39 A, demonstrating a smooth waveform with minimal ripples due to the filtering effect of the LC filter. This stable current flow is crucial for maintaining reliable operation of the motor. Despite slight deviations from the targeted current of 35 A, the achieved value of 34.39 A with the LC filter remains within acceptable operational limits. In comparison, the chopper circuit without the LC filter exhibited an average output current of 31.24 A, underscoring the significant improvement in current stability and overall system performance achieved through the integration of the LC filter.



**Figure 4.** Output current of the chopper circuit with LC filter

Furthermore, integrating the LC filter leads to substantial enhancements in the boost converter's efficiency. This improvement is critical as it reduces power losses within the converter, resulting in more efficient energy transfer from the input to the output. By smoothing out voltage fluctuations and minimizing ripple, the LC filter ensures a more stable and reliable power supply to the motor. This enhanced stability not only improves the overall performance of the motor but also prolongs its operational lifespan by reducing stress on its components. Therefore, the result of this study yielded that, the boost converter's efficiency increases from 81.21% to 94.18% with the incorporation of the LC filter reflects a significant technological advancement in optimizing power conversion processes for industrial and energy-efficient applications.

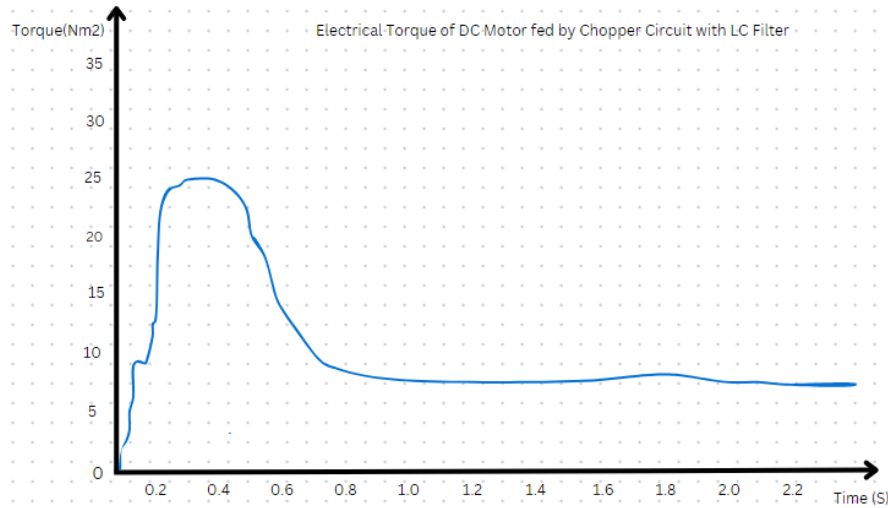
Figure 5 presents the simulation results showing the speed response of a separately excited DC motor when powered by a chopper circuit with an LC filter, analyzed using MATLAB/Simulink. The achieved motor speed is measured at 1205 rpm, which closely aligns with the target speed of 1200 rpm. This slight deviation of only 5 rpm falls within an acceptable margin of error and is unlikely to adversely affect the motor's performance. Furthermore, the terminal voltage of the DC motor exhibits minimal ripples, indicating smooth operation with negligible harmonic content. The absence of significant harmonics corroborates the stability of the motor's operational parameters. Comparatively, the chopper circuit without the LC filter resulted in a lower motor speed of 1103 rpm, highlighting the significant improvement achieved by integrating the LC filter. This enhancement not only ensures precise speed control but also contributes to overall motor efficiency and longevity, making the system more reliable for practical applications.



**Figure 5.** Speed of DC Motor Response when fed by Chopper Circuit with LC Filter

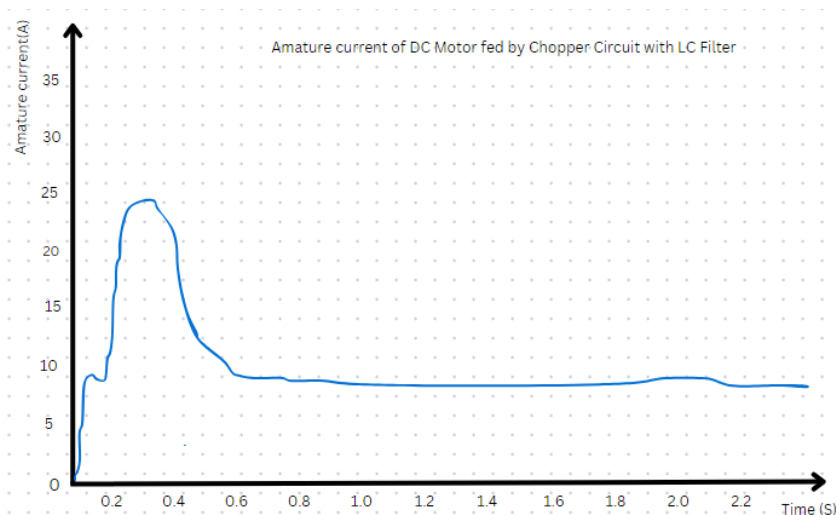
Figure 6 illustrates the electrical torque response of a DC motor when driven by a chopper circuit equipped with an LC filter, as simulated using MATLAB/Simulink. The torque response shows a smooth profile without noticeable ripples, indicating efficient operation with minimal mechanical and electrical losses as Figure 6 depicted. This improvement is crucial as it enhances the overall efficiency of the motor system. Specifically, the motor equipped with the LC filter achieves an electrical torque of 6.907 Nm<sup>2</sup>, compared to 5.85 Nm<sup>2</sup> without the filter. This increase highlights the significant enhancement in torque delivery and operational stability achieved through the integration of the LC filter. By minimizing energy losses and ensuring smoother torque delivery, the LC filter contributes to improved motor performance and reliability in various industrial applications.





**Figure 6.** Electrical Torque of DC Motor when fed by Chopper Circuit with LC Filter

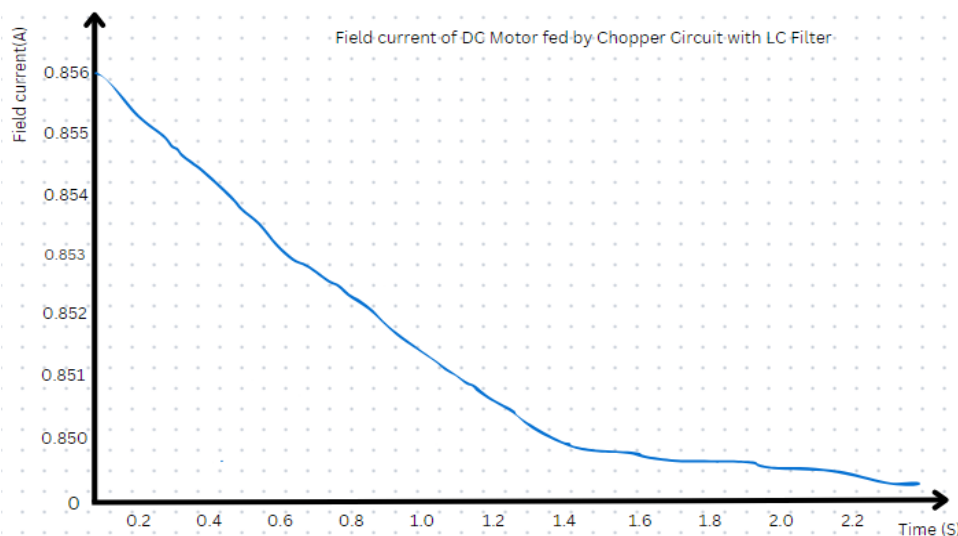
Figure 7 depicts the armature current response of a DC motor when powered by a chopper circuit with an LC filter, analysed through MATLAB/Simulink simulations. The simulation results indicate that the armature current of the motor, measured at 8.537A, exhibits exceptional smoothness due to the integration of the LC filter. This smooth response, as visually depicted in Figure 7, is a direct result of the LC filter's ability to suppress voltage and current ripples, thereby reducing harmonic distortion in the motor's operation. The absence of significant ripples and harmonics enhances the motor's operational efficiency and reliability, ensuring a high-quality output. Comparatively, the chopper circuit without the LC filter resulted in an armature current of 8.032 A, highlighting the significant improvement achieved by incorporating the LC filter. This enhancement not only ensures smoother current flow but also contributes to minimizing energy losses and improving overall motor performance. The observed increase in armature current with the LC filter demonstrates its effectiveness in optimizing motor operation, making it suitable for applications where precise control and efficiency are paramount.



**Figure 7.** Armature Current of the DC Motor when fed by Chopper Circuit with LC Filter

Field current response of a separately excited DC motor when powered by a chopper circuit with an LC filter was presented in Figure 8. The average field current is measured at 0.8532A, as observed in the Simulink scope graph of Figure 8. This result indicates that both configurations, with and without the LC filter, achieve the same field current value. The consistent field current of 0.8532 A, regardless of the presence of the LC filter, suggests that the filter does not significantly affect the field current in this simulation scenario. The field

current remains stable and within expected operational parameters, demonstrating the robustness and reliability of the motor's field control system. While the LC filter primarily influences the voltage and current smoothness in other aspects of motor operation, its negligible impact on field current suggests that the motor's magnetic field regulation remains stable and unaffected by the filter.



**Figure 8.** Field Current of DC Motor when fed by Chopper Circuit with LC Filter

The efficiency of a separately excited DC motor, as depicted in the simulation results, shows a significant improvement with the incorporation of an LC filter in the chopper circuit, as analysed through MATLAB/Simulink. The motor's efficiency without the LC filter is recorded at 68.32%, whereas with the LC filter, the efficiency rises notably to 85.13%. This enhancement indicates the effectiveness of the LC filter in optimizing the motor's performance by reducing losses and improving energy conversion efficiency. The increase in efficiency from 68.32% to 85.13% can be attributed to several factors facilitated by the LC filter. Firstly, the filter minimizes voltage and current ripples, resulting in smoother operation and reduced losses within the motor. This smoother operation translates into less energy dissipation as heat, thereby improving overall efficiency. Secondly, the LC filter helps maintain a stable and consistent power supply to the motor, enhancing its ability to deliver torque and maintain speed under varying load conditions. From a practical standpoint, the higher efficiency achieved with the LC filter not only reduces operational costs but also prolongs the motor's lifespan by minimizing thermal stress and mechanical wear. Moreover, the improved efficiency contributes to greater system reliability and stability, making the motor suitable for demanding industrial applications where precision and consistency are critical.

#### 4. Conclusion

In conclusion, the integration of the LC filter in the boost converter circuit significantly improves the performance of both the converter and the separately excited DC motor. The findings demonstrate that the LC filter effectively mitigates ripple in the output voltage and current, resulting in smoother power delivery to the motor. This leads to notable enhancements in system efficiency, with the boost converter efficiency increasing from 81.21% to 94.18% and the motor efficiency rising from 68.32% to 85.13% with the LC filter. Additionally, the LC filter contributes to improved motor performance, as indicated by the increase in motor speed and torque. Moving forward, future research could focus on optimizing the design of the LC filter for further efficiency gains and exploring different configurations and parameters to advance the field of power electronics and motor control.

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