Project Report (Group No. 8)
Design a battery and ultracapacitor based bidirectional converter with inverter for PMSM system for regenerative braking
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submitted

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1 Contribution

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- Exploring potential applications of the technology beyond regenerative braking.
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- simulation studies to evaluate the performance of the regenerative braking system.

2 Chapter 1: Introduction

Regenerative braking in Permanent Magnet Synchronous Motor (PMSM) systems captures kinetic energy during deceleration and stores it for later use, improving efficiency and range. This can be achieved with a battery and ultracapacitor hybrid energy storage system (HESS) coupled with a bidirectional converter and inverter.

The permanent-magnet synchronous motor (PMSM) is widely adopted as the traction motor in electric vehicles (EV) due to its high efficiency and high torque density. Vector control, also called field-oriented control (FOC), is a popular and powerful method in electrical drive applications. This control strategy is used to effectively control the PMSM motor torque and flux in order to force the motor to accurately track the command trajectory regardless of machine and load parameter variations, or any other external disturbances [1].

HESS comprising of battery and ultracapacitor feeding a dual input bidirectional DC-DC converter controls the power flow as per the control signals from the accelerator and brake pedals in both discharging (traction) mode and charging (regenerative braking) mode of operation. In traction mode, the inverter draws required power demanded by the load while the DC-DC converter maintains the DC link voltage by drawing required power from the source. In regeneration mode also, the DC link voltage is maintained constant by transferring the regenerated power to the ultracapacitor [2].

2.1 Objectives

- Utilize the high power density of ultracapacitors for efficient energy transfer and peak power delivery, improving overall system efficiency.
- Reduce high-current charging/discharging cycles on the battery by using the ultracapacitor as a buffer for peak power demands.
- The converter is designed to handle the high power requirements of the PMSM during regenerative braking and ensure efficient energy transfer between the energy source and the load.
- Develop and optimize a novel bidirectional converter topology for efficient power management between the battery, ultracapacitor, and DC link.

2.2 Schematic block diagram :

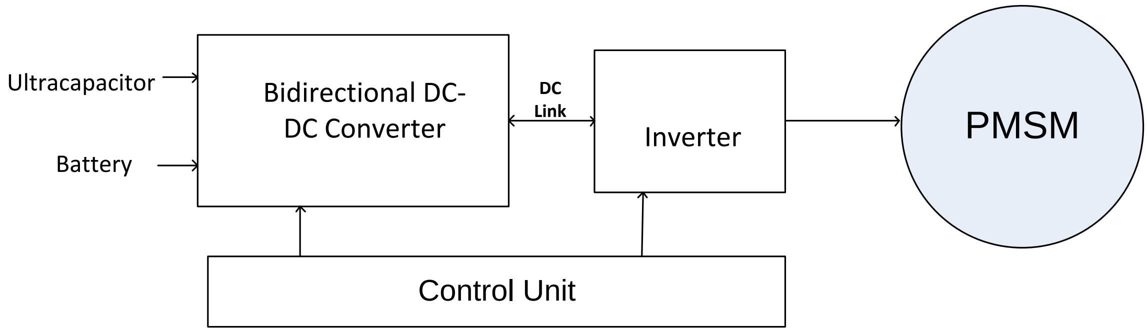

Figure 1: Block Diagram of DC-DC Bidirectional connverter [1].

2.3 Theory relevant to the project

2.3.1 System components :

- **Bidirectional DC-DC Converter:** This converter connects the battery and ultracapacitor bank to the DC link. It handles power flow in both directions.
- **Boost mode:** During regenerative braking, the converter steps up the voltage from the PMSM to charge the ultracapacitor quickly.
- **Buck mode:** When accelerating or requiring power, the converter steps down the voltage from the battery or ultracapacitor to deliver power to the DC link.
- **DC Link Capacitor:** This capacitor smooths out DC voltage fluctuations on the DC link, ensuring stable operation for the inverter.
- **Inverter:** This component converts the DC voltage from the link into a three-phase AC voltage to drive the PMSM. It employs Pulse Width Modulation (PWM) techniques to control the motor speed and torque.

2.3.2 DC-DC Bidirectional Converter And Its Controller Design:

Function of the bidirectional DC-DC converter is to control power flow from the source to load during traction and from load to source during regeneration. It also controls the power sharing between battery and UC power converters should have high efficiency, low current ripple drawn from the source, buck and boost capability and control of the bidirectional power flow irrespective of the input voltage variations.

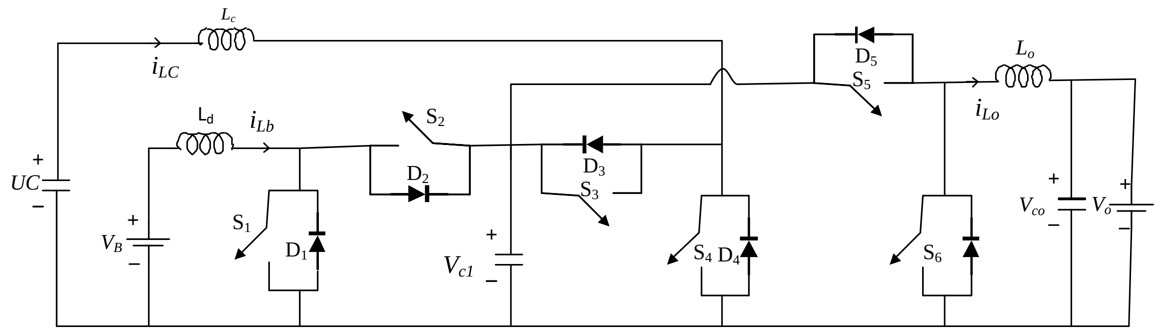

Figure 2: DC-DC Bidirectional Converter(SEPIC converter) [2].

2.3.3 DC Converter Controller

Power flow from source to load is discharging mode with respect to battery or traction mode with respect to motor, while power flow from load to source is charging mode with respect to battery or regenerative braking mode with respect to motor. Switches S1, S4 and S5 are in PWM mode of operation and controls the power flow during the traction mode. Battery will be sharing the base load and the reference value of battery current is set using a battery current limiter which is fixed as per the driving cycle. Actual battery current is compared with the reference value and the error signal through a PI controller controls the switch S1 .

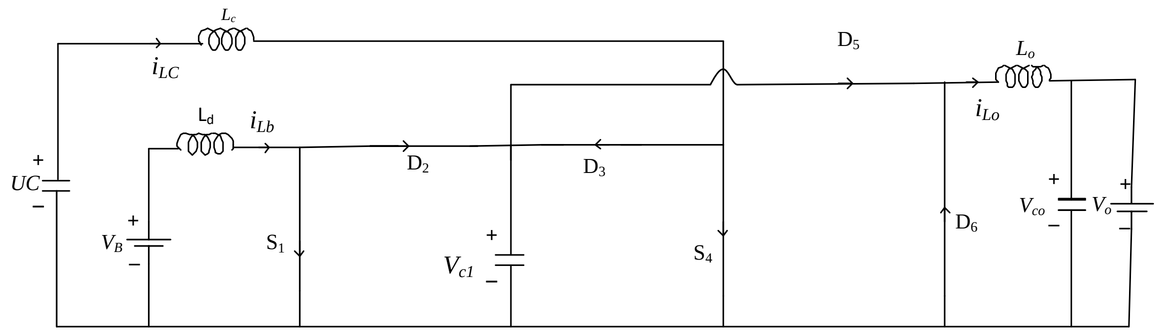

Figure 3: DC-DC Bidirectional Converter showing the forward power flow [2].

If the load current is beyond the battery limit, VCI will reduce and the remaining current is shared by UC which is controlled by the switch S4. The output voltage is maintained constant by the voltage control loop of switch S5. During forward power flow, phase 1 acts as boost converter with the condition, battery voltage greater than its nominal value and intermediate capacitor voltage less than its reference value . Phase 2 converter is in buck mode with $V_b > (V_{nom})$, $VCI < VCI_{ref}$ and the output voltage less than its reference value $Vo < (Vo_{ref})$. During regenerative braking mode, switches S2, S3 and S6 are in PWM mode of operation and controls the reverse power flow. Phase 1 acts as buck converter with the condition, battery voltage less than its nominal value $V_b < (V_{nom})$ and intermediate capacitor voltage greater than its reference value $VCI > (VCI_{ref})$. Phase 2 converter is in the boost mode with $V_b < (V_{nom})$, $VCI > (VCI_{ref})$ and the output voltage greater than its reference value $Vo > (Vo_{ref})$.

2.3.4 Regenerative Braking of the PMSM Under FOC

In conventional passive dynamic braking the kinetic energy of electric machines is dissipated through the armature coils and the additional braking resistors. The principle of the regenerative braking with the voltage-source inverter is similar to that of the conventional dynamic braking, however; the additional resistors are eliminated and no additional power switches are used. According to the driving conditions, the braking process can be classified as either constant speed braking or variable speed braking. The constant speed braking is usually required during the downhill road driving, while the variable speed braking often occurs during the general deceleration process.

2.3.5 System Setup

Figure 1 shows the general topology used in electric vehicle applications with hybrid energy storage, where the mechanical load is typically coupled to a Permanent-Magnet Synchronous Machine supplied by a battery source through an inverter. An ultracapacitor module is used as an auxiliary power source connected through a bi-directional dc-dc converter to the dc-link, thus making it possible to obtain an optimized charge/discharge operation mode

2.3.6 Regenerative Braking principle of the PMSM

The stator phase currents are measured and converted into a complex vector. This current vector is then transformed to a coordinate system rotating with the rotor of the machine. The real x-axis component of the stator current vector id, in this rotor flux-oriented coordinate system, is used to control the rotor flux linkage. The imaginary y-axis component iq is used to control the motor torque. For the PMSM, maximum torque–current control can be achieved by holding the d-axis current at zero (id = 0). Electric braking control, based on FOC, is realized by requesting a negative q-axis current according to the braking torque demanded, or by controlling the speed to follow a ramp reference and gradually approach zero The input power and the electromagnetic power can be expressed as

$$P_{in} = V_d I_d + V_q I_q \tag{1}$$

$$P_{em} = T_{em} \cdot \omega \tag{2}$$

$$T_{em} = \frac{3}{2}\frac{p}{2}\lambda_{pm}.i_q \tag{3}$$

where, i_d and i_q are the d-axis and q-axis current components, v_d and v_q are the d-axis and q-axis voltage components, ω is the motor speed, T_{em} is the electromagnetic torque, λ_{pm} is the permanent magnet flux and p is the number of poles

The electric machine power losses are given as

$$P_{loss} = i_d^2 R + i_q^2 R \tag{4}$$

Where, R is the per-phase stator resistance. By balancing the input and output power

$$P_{in} = P_{em} + P_{loss} \tag{5}$$

$$P_{in} = \frac{3}{2}.\frac{p}{2}\lambda_{pm}.i_q \cdot \omega + R(i_d^2 R + i_q^2 R) \tag{6}$$

To find the regions of regenerative braking, P_{in} is set to 0. This means that no power is being drawn from the DC source.

$$i_q = \frac{-\frac{3}{2}\frac{p}{2}\lambda_{pm} \cdot \omega \pm \sqrt{\left(\frac{3}{2}\frac{p}{2}\lambda_{pm}\omega\right)^2}}{2R} \tag{7}$$

The equivalent electromagnetic torque is given as

$$T_{em} = \frac{3}{2}\frac{p}{2}\lambda_{pm}\frac{-\frac{3}{2}\frac{p}{2}\lambda_{pm} \cdot \omega \pm \sqrt{\left(\frac{3}{2}\frac{p}{2}\lambda_{pm}\omega\right)^2}}{2R} \tag{8}$$

This equation describes the electromagnetic torque inside the regenerative braking region. To find the boundaries of this region, the above equation is solved for the maximum and minimum braking torque.

2.3.7 Hybrid Energy Storage System

High energy efficiency, high range per charge and good dynamic response are the main requirements of an EV which can be attained by using energy sources with high power density, high energy density and by appropriate power management. The traction load demands peaky power during acceleration and climbing up a gradient, which can be met by paralleling more cells, but it will increase the volume and weight . UC with high power density keeps the battery current within limit so that the power and energy demand of the load is met with a lower battery size. An HESS with a combination of battery having high energy density and UC having high power density will be appropriate for EV application. Also, UC improves dynamic response of the vehicle and work efficiently due to its ability to accept high current during regenerative braking.

The battery life will be improved, thermal management will be easier and regeneration will be more effective thus improving the driving range . But the challenge will be the complex control of power shared by both, where the load condition is unpredictable.

2.3.8 Ultra Capacitor

Ultracapacitors bridge the gap between batteries and traditional capacitors. They offer high power density and fast charge/discharge capabilities, making them suitable for applications requiring short bursts of power. However, their limited energy density makes them less suitable for situations requiring long-term energy storage.

2.4 Simulation Setup

The battery which is in a passive state collects energy from regenerative braking. This separates thermal management and allows the battery to operate safely in high current conditions. In addition to cooling the battery, it can also warm up at low temperatures to reach the desired performance limits. Take. Also, balancing the cells of the battery system is a problem related to battery life. In the absence of a balancing system, individual voltage differs from its original voltage state. Then, during operation, the AH capacity of the entire battery drops sharply, which can cause the complete battery system to fail. Mostly it happens when the battery is used for fast charging and fast discharging. Traditional HESS connects UCs via DC / DC converters to meet real-time peak power requirements for powertrain control. Which needs the same capacity of UC and battery, or maybe more than higher performance than required. The revised HESS works in another way.

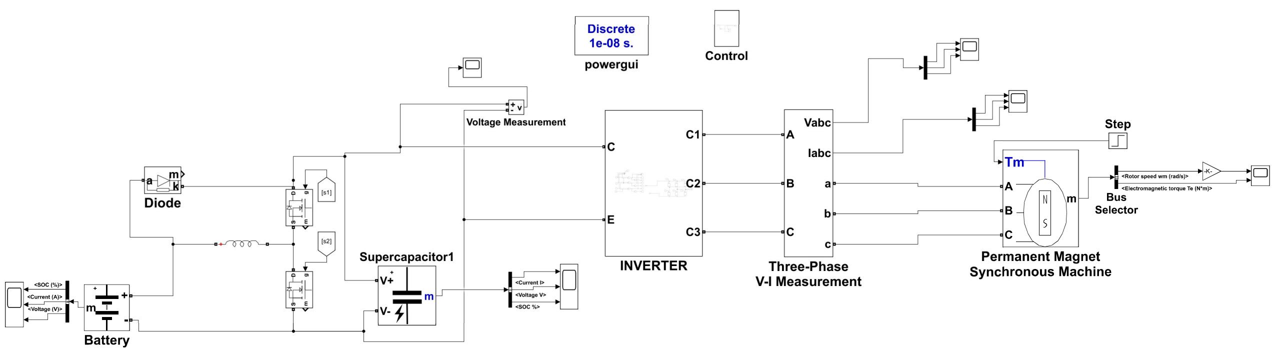

Figure 4: Simulation Setup (Open Loop).

The project's simulation setup is depicted in the figure 4. The battery is connected to the motor via DC-DC here. converter and ultracapacitor is connected with hybrid combination to the motor. Battery is connected to the converter via forward bias switch so the reverse current will not flow back to the battery. The inverter is connected to the PMSM motor. The control block is providing supply regulation. The voltage block is connected across the dc link and ultracapacitor also where we have measured SOC, voltage, and current across the DC link.

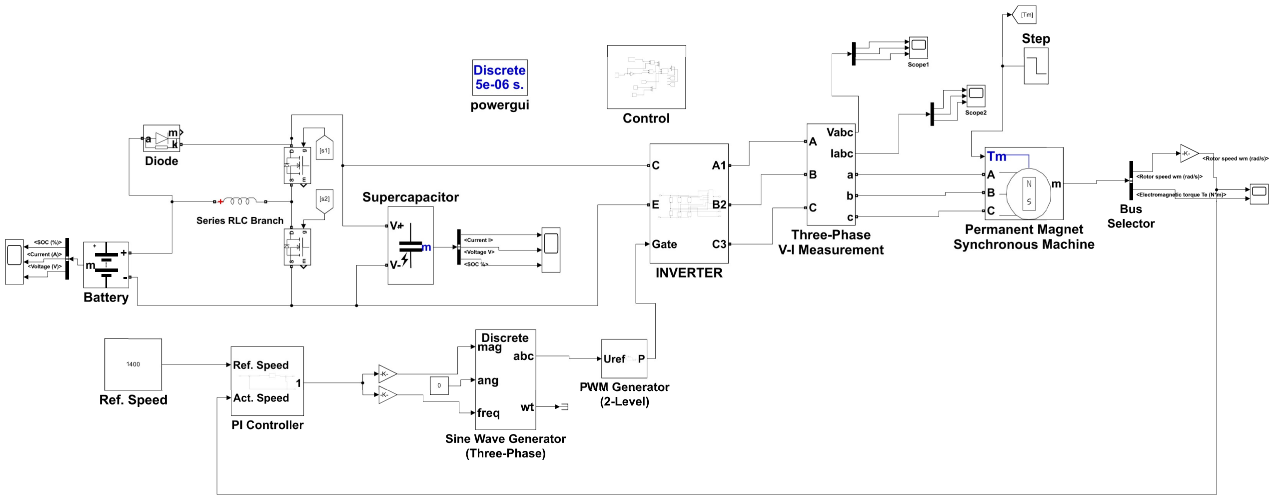

Figure 5: Simulation Setup (Closed Loop) [3].

2.4.1 Inverter Block

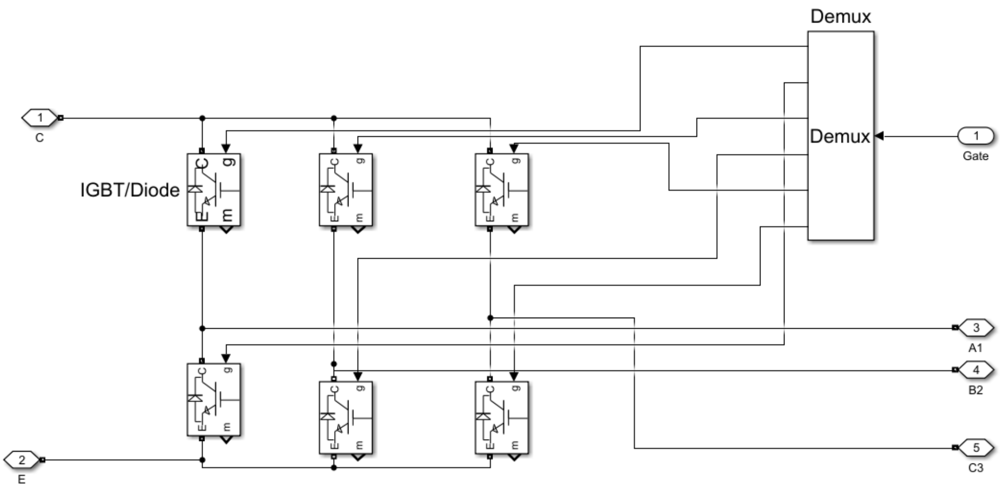

Figure 6: Inverter Block

The inverter block is connected between Dc-Dc converter and PMSM inverter block do energy conversion, such as DC to AC, at the desired frequency and voltage. o/p. This can be classified based on the power source as well as the topology of the power circuit. As a result, they are classified into two types: voltage source inverter and CSI inverter (current source inverter).
The VSI type inverter has a lower impedance DC voltage source at the inverter's input terminals. CSI inverters have a high impedance DC current source. The circuit, operation, and applications

of a three-phase inverter are described in this article. Three-phase inverters are made up of three inverter switches, each of which is connected to load.Waveform has zero voltage stage during its inverting stage. The three switches can be synced for the basic control system so that a single switch operates at every 60 degrees of the basic o/p waveform, resulting in a six-step line-to-line o/p waveform.

2.4.2 Inverter Output Voltage

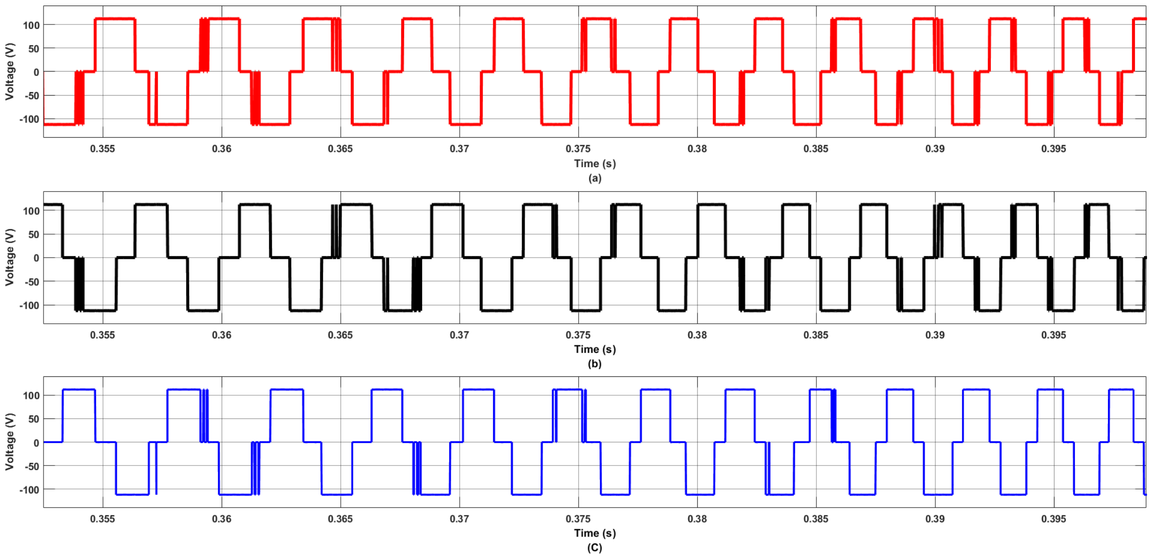

Figure 7: (a) Vab ; (b) Vbc ; (c) Vca.

2.4.3 Inverter Output current

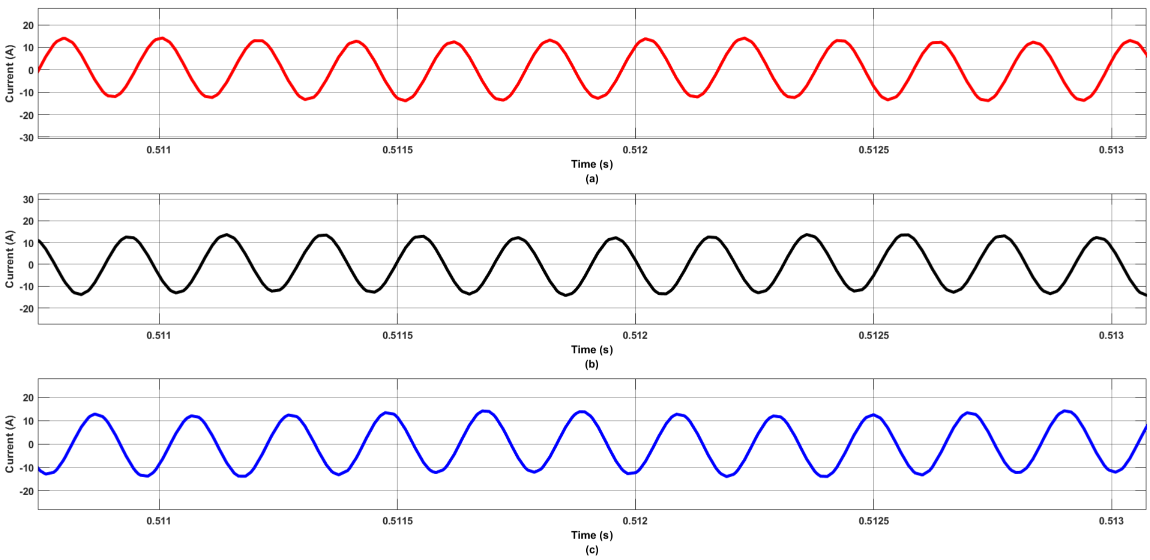

Figure 8: (a) Ia ; (b) Ib ; (c) Ic.

2.4.4 PMSM Scope Output

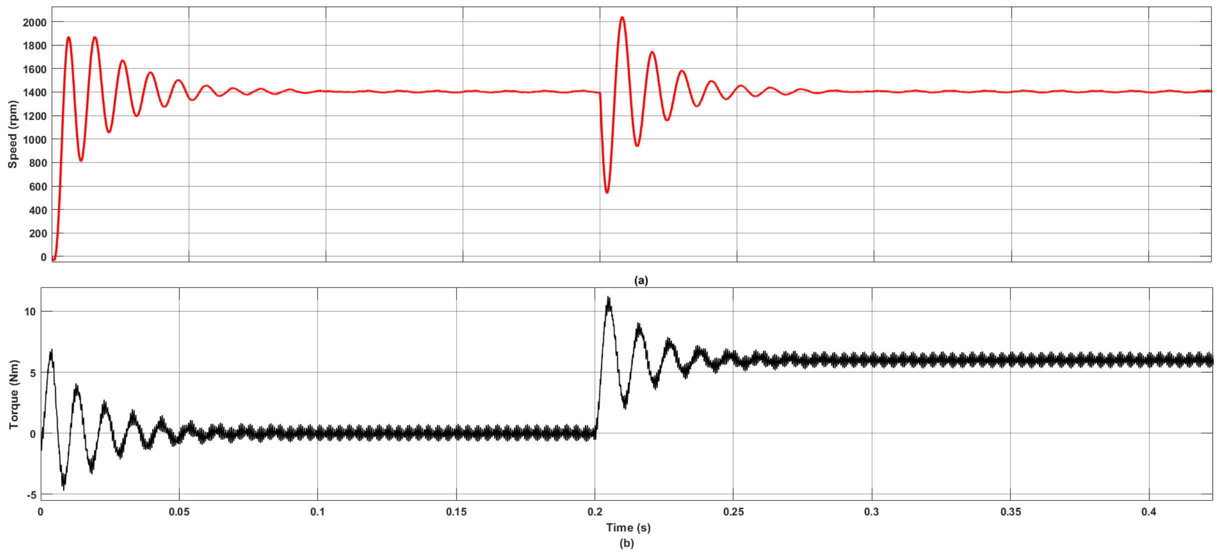

Figure 9: (a) Rotor Speed ; (b) Electromagnetic Torque.

2.4.5 Controller Output

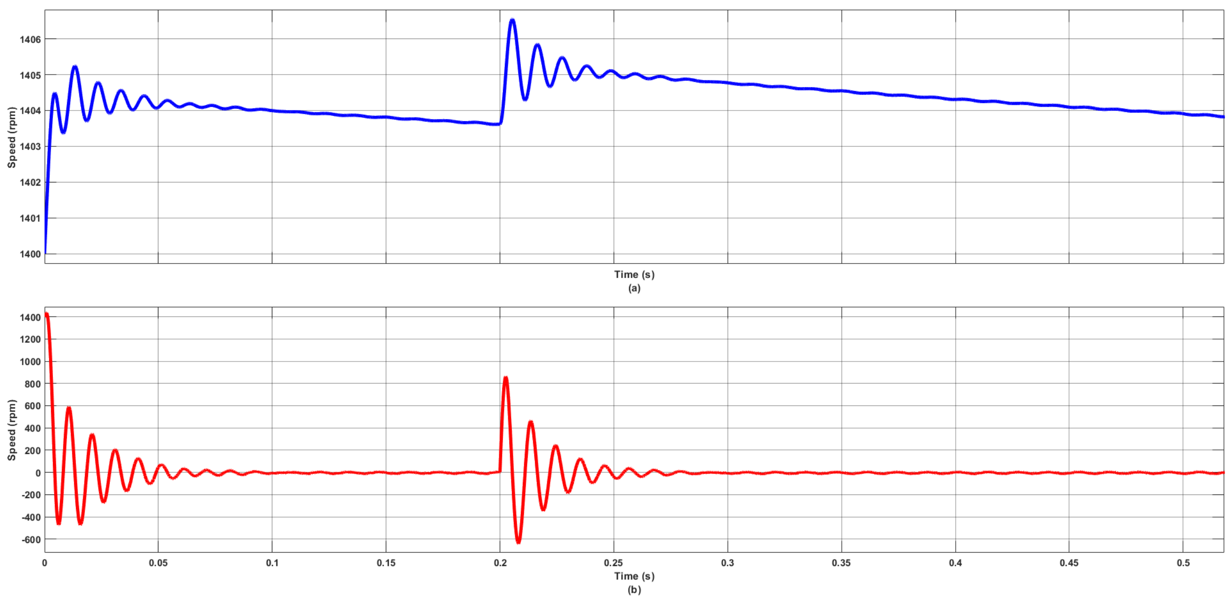

Figure 10: (a) PI controller output ; (b) Error output.

2.5 Conclusion and future scope

2.5.1 Conclusion :

A design for a battery and ultracapacitor based bidirectional converter with inverter for a PMSM system offers promising potential for improving the efficiency and performance of electric vehicles and other electric traction systems. Combining the high power density of ultracapacitors with the energy storage capacity of batteries allows for: Recovering and reutilizing kinetic energy during braking extends range and reduces reliance on grid electricity. Utilizing ultracapacitors' fast power delivery enables faster acceleration and smoother operation.

2.5.2 Future Scope :

While the basic design presents a compelling approach, ongoing research and development aim to further refine and improve the technology:

- Exploring new converter designs with higher efficiency, power density, and wider voltage conversion ranges
- Implementing more sophisticated algorithms for optimized energy management, precise motor control, and enhanced system protection.

2.6 References

References

[1] Andrew Adib and Rached Dhaouadi. Performance Analysis of Regenerative Braking in Permanent Magnet Synchronous Motor Drives. *Advances in Science, Technology and Engineering Systems Journal*, 3(1):460–466, 2018.

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