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Cuk Converter Fed Electric Vehicles

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Abstract: *This paper describes the operation of a separately excited dc motor for EV application. Battery fed electric vehicles (BFEVs) are required to function in two different modes namely: acceleration mode and braking (regenerative) mode. During acceleration and normal modes the power flow is from battery to motor whereas during braking or regenerative mode the kinetic energy of the motor is converted into electrical energy and fed back to battery. Four quadrant and two quadrant operation of electric vehicles are implemented in this paper.*
Keywords*: Battery, Bidirectional DC-DC Converter, Cuk Converter , PI Controller, Separately Excited DC Motor*

I. Introduction

Petroleum resources across the world is depleting at a high rate due to the large dependency of the transportation sector on petroleum as the primary fuel. Also due to this, there is a vast greenhouse gas emission that is degrading the quality of air and causing harm to life and environment. This has aroused a tremendous interest for the design of the vehicles with lesser or no dependency on the petroleum resources. And therefore the alternate propulsion technologies have been increasingly pursued by the automobile industries and this has led to the increased development rate of the of the Hybrid Electric Vehicle (HEV) or Battery Fed Electric Vehicle (BFEV) technology in the past two decades. Battery-powered electric vehicles (BEVs) seem like an ideal solution to deal with the energy crisis and global warming since they have zero oil consumption and zero emissions. However, factors such as high initial cost, short driving range, and long charging time have highlighted their limitations. But since then due to the better development in the ICE technologies and the cheaper petroleum prices made the ICE run vehicle a better option than a HEV. An HEV unlike conventional vehicle, which depends solely on the ICE engine for the traction power, utilizes electrical energy storage in combination with the ICE to provide the required traction power. Thus it facilitates the improvement in the energy conversion of the vehicle thereby increasing the efficiency and drivability and at the same time reducing the emissions. Furthermore the integration of the electrical storage system also makes the provision for the regeneration during braking which can further boost up the efficiency of the overall system. In future, a number of instantaneous changes in ICE technology, in energy storage device and energy conversion system, the efficiency of BFEVs will be increased that will attract more consumer.

One of the main considerations for the BFEV drives is to improve the efficiency of the motor drive. This can be done by increasing the voltage level of ESS and thereby reducing the high currents and thus the associated losses. For this purpose, a bidirectional DC-DC converter can be used. Bidirectional DC-DC converters boost up the voltage level of the electrical storage system to the higher voltage level and thereby reducing the current level and hence the losses. Also Bidirectional DC-DC converter facilitates the provision for the reverse power flow back into the ESS during regenerative braking and hence further increasing the efficiency. This two features of the Bidirectional DC-DC converter makes it a better option for power conversion in the BFEV thereby reducing overall cost, size and weight of the system along with increasing efficiency and achieving regenerative energy.

DC motors are used in many applications like electric railway traction and many more industrial fields such as rolling mills, paper industries etc , because they can provide a high starting torque. The big and practical advantage of DC motor over AC motors that the range of speed control. In DC motor we can control the speed below and above the rated speed by using different methods and techniques. The speed control above the rated speed can be achieved by using field current control method and below the rated speed by varying the armature voltage known as armature voltage control method. The speed of DC motor is directly proportional to the armature voltage (Va) and inversely proportional to the field current (If). In armature voltage control, the range of speed control is from zero to rated speed .While in the field control, the speed control range from constant reference speed up to 120%-130% rated speed can be achieved but with loss of the motor developed torque.

Recently bi-directional dc-dc converters are widely researched and developed for various applications. In case of the battery fed electric vehicles (BFEVs), electric energy flows between motor and battery side. For achieving zero emission, the vehicle can be powered only by batteries or other electrical energy sources. The use of a Bi-directional dc-dc converter fed dc motor drive devoted to electric vehicles (EVs) application allows a suitable control of both motoring and regenerative braking operations, and it can contribute to a significant increase in the drive system overall efficiency. In this paper a cuk converter fed PI controlled bi-directional DC-DC converter is used for the operation of a four wheeled battery fed electric vehicle. It has four quadrant of operation. As the circuit became more complex, we have gone to another circuit for the same operation by replacing the bi-directional converter by a two quadrant chopper. It can be used for the operation of two wheeled vehicles as it can provides only forward motoring and forward breaking modes. Thus the conventional system uses a bi-directional DC-DC converter along with a boost converter but this paper imparts into a new idea of using cuk converter. This paper also gives an idea of using cuk converter without a bi-directional converter to enhance the performance of two wheeled electric vehicles.

II. Literature Survey

1. BFEV

BFEV consist of bi-directional DC-DC converter, boost converter, battery, DC machine and controlling unit, where heart of the BFEVs is DC-DC bidirectional converter. There are two energy sources namely, battery section and generator section in this system. According to power electronics point of view, when power is transferred between two energy sources, an efficient energy interference system or power chain has to be developed. For hybrid vehicles, the dc drive link and the battery may be at different voltage levels. DC link may be at high voltage stage to have higher efficiency on the motor and batteries are at low voltage stage. Therefore, an efficient interfacing system between the drives dc link and the battery is essential. In BFEVs, the power stream is from battery to motor over acceleration and normal modes, while the kinetic energy of the motor is renewed into electrical energy and fed back to battery during regenerative mode. The interfacing system will control these two modes. Recently, BFEV system is widely researched, where the efficiency and performance improvement of the converter (especially, bi-directional DC-DC converter) is the key concentration of researchers. Researcher offers soft switching technique to increase the transfer efficiency for bidirectional DC-DC converter. Bi-directional DC-DC converters have been reported using coupled inductor intended for soft-switching technique with hysteresis current controller. Zero-current-switched (ZCS) and zero voltage- switched (ZVS) techniques are established for minimizing switching losses and to improve the reliability of bi-directional DC-DC converter. During regenerative mode, the performance of overall power transfer through the electrical circuit of BFEV depends on the effective combination of step up converter and bi-directional DC-DC converter. For efficient operation researchers mainly analyze the performance of BFEVs by the combination of boost converter and bi-directional DC-DC converter. A high ripple output current of the boost converter is the main drawback of this method. Therefore, this paper proposes a new design of converter circuits which combines a cuk and a PI controlled DC-DC bi-directional converter to provide the desired battery voltage for BFEV applications.

2. BIDIRECTIONAL DC-DC CONVERTERS

Bidirectional DC-DC converters serves the purpose of stepping up or stepping down the voltage level between its input and output along with the capability of power flow in both the directions. Bidirectional DC-DC converters have attracted a great deal of applications in the area of the energy storage systems for Hybrid vehicles, Renewable energy storage systems, Uninterruptable power supplies and Fuel cell storage systems. Traditionally they were used for the motor drives for the speed control and regenerative braking. Bidirectional DC-DC converters are employed when the DC bus voltage regulation has to be achieved along with the power flow capability in both the direction. These systems cannot serve as a standalone system for power supply because of the large fluctuations and therefore these systems are always backed up and supported by the auxiliary sources which are rechargeable such as battery units or super capacitors. This sources supplement the main system at the time of energy deficit to provide the power at regulated level and gets recharged through main system at the time of surplus power generation or at their lower threshold level of discharge. Therefore a bidirectional DC-DC converter is needed to be able to allow power flow in both the directions at the regulated level. Likewise in HEVs, bidirectional DC-DC converters are employed to link up the high voltage DC bus to the hybrid electrical storage system (usually a combination of the battery or a fuel cell with the super capacitor). Here they are needed to regulate the power supply to the motor drive to assist the ICE according to the traction power demanded.

3. STEP UP CONVERTER

3.1 Boost converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

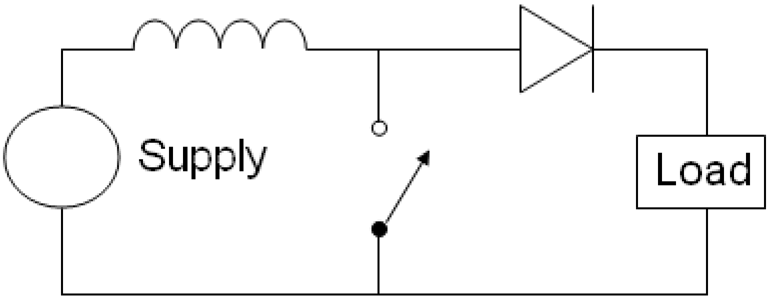

Fig 1: basic structure of boost converter

Figure 1 shows the basic schematic of a boost converter. The switch is typically a MOSFET, IGBT or BJT. Power for the boost converter can come from any suitable DC sources, such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it "steps up" the source voltage. Since power must be conserved, the output current is lower than the source current.

3.2 Cuk converter

The Cuk converter is a type of DC/DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. Similar to the buck–boost converter with inverting topology, the output voltage of non-isolated cuk is typically also inverting, and can be lower or higher than the input. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. It is named after Slobodan cuk of the California Institute of Technology, who first presented the design. There are variations on the basic cuk converter. For example, the coils may share single magnetic core, which drops the output ripple, and adds efficiency. Because the power transfer flows continuously via the capacitor, this type of switcher has minimized EMI radiation. The cuk converter allows energy to flow bi-directionally by using a diode and a switch. Figure 2 shows the basic structure of cuk converter.

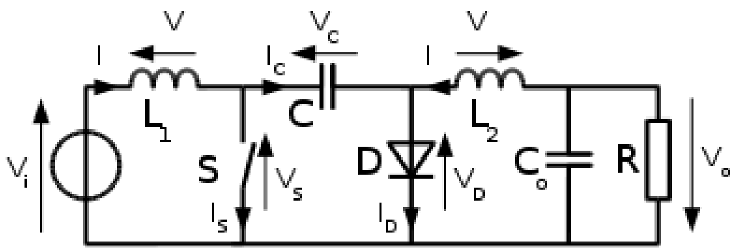

Fig 2: cuk converter**.**

III. Bi-Directional Dc-Dc Converter

1. THE NEED FOR A BI-DIRECTIONAL DC-DC CONVERTER IN THE BFEV IS DUE TO THE FOLLOWING REASONS

- High efficiency
- Light weight and compact size
- Lower electromagnetic interference
- Controlled power flow in spite of wide input voltage variation

To be able to recharge the electrical energy storage system during the re-generative braking, and hence therefore there should be the provision of bidirectional power flow.

2. CONTROL STRATEGY

The control circuit of the bidirectional converter is shown in Fig.3 to control the speed of the dc drive; one possible control option is to control the output voltage of the bidirectional converter. To control the output voltage of the bidirectional converter for driving the vehicle at desired speed and to provide fast response without oscillations to rapid speed changes a PI controller is used and it shows satisfactory result[2]. In this control technique the motor speed ω_m is sensed and compared with a reference speed ω_{ref}. The error signal is processed through the PI controller. The signal thus obtained is compared with a high frequency saw tooth signal equal to switching frequency to generate pulse width modulated (PWM) control signals.

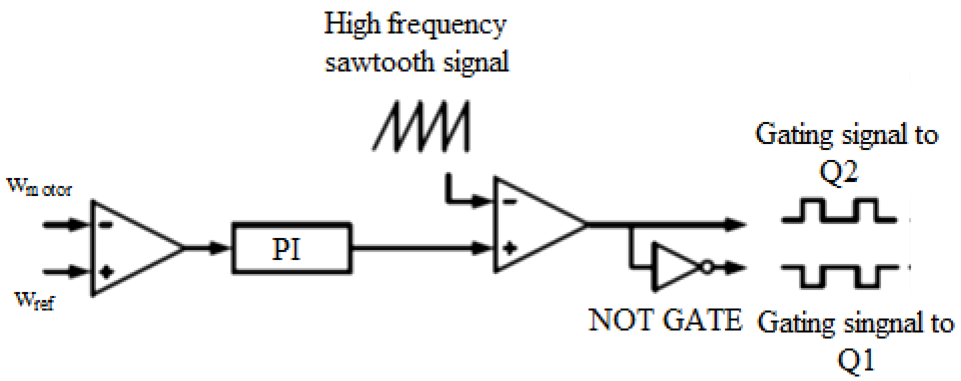

Fig. 3: Control strategy of the bidirectional dc-dc converter.

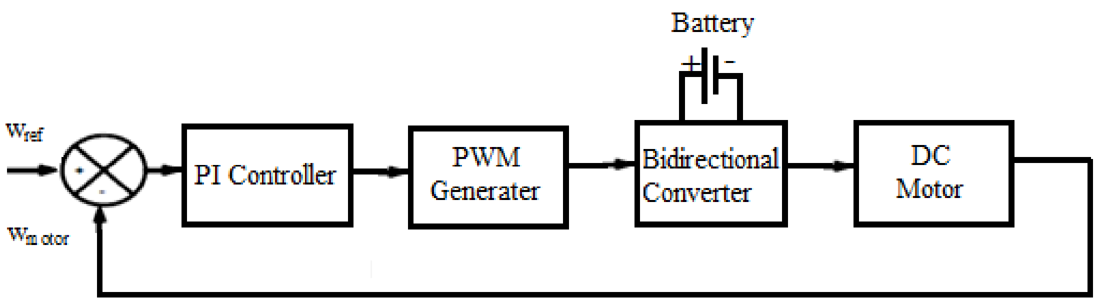

Fig. 4: Closed loop operation of the drive.

The block diagram of feedback speed control system for DC motor drive is shown in Figure; the control objective is to make the motor speed follow the reference input speed change by designing an appropriate controller. The proportional-integral(PI) controller is used to reduce or eliminate the steady state error between the measured motor speed (ω_{motor}) and the reference speed (ω_{ref}) to be tracked.

3. PROBLEMS WITH BIDIRECTIONAL DC TO DC CONVERTER

- Makes circuit more complex
- Introduces more amount of ripples
- Reduce the magnitude of quantities
- Make control complex

IV. Dc Motor Control

A DC motor may operate in one or more modes (or quadrant) in variable speed applications. The major advantage of using DC motor is that the ease of its control. The speed of the DC motor is controlled by applying a variable DC input for below rated speed control. For above rated speeds, the motor is controlled by applying variable current through its field winding.[3] For reversing the direction of rotation, either polarity of the supply voltage (which is applied to armature terminals) or the direction of field current has to be changed. By using DC motors, it is possible to obtain smooth speed control over a wide range in clockwise as well as anti-clockwise directions.

1. DC MOTOR

The torque of a DC motor is proportional to the armature current which in turn depends on the difference between back EMF and applied voltage. Therefore, it is possible to make the motor to develop positive or negative torque simply by controlling the applied voltage to a greater or lesser than the back EMF. Thus an armature controlled DC machine is inherently capable of operating different modes or quadrants, generally it is known as four-quadrant operation of a motor. In multi-quadrant operation or four quadrant operation, motor accelerates or decelerates depending on whether motor torque is lesser or greater than load torque. During motor acceleration, it should supply not only the load torque, but an additional component of load current to overcome the inertia. Motor positive torque produces the acceleration in forward direction. In this, the motor speed is positive when the motor is rotating in forward direction. During motor deceleration, the resultant or dynamic torque has a negative sign. This torque assists with motor developed torque and maintains the motion by extracting the energy from stored energy. Hence the motor torque is considered as negative if it produces deceleration. A motor can be controlled in such a way that it operates in two cases; motor action and braking action. Motor action converts the electric energy into mechanical energy and it produces forward motion, hence it called as motoring action, whereas braking action converts mechanical energy to electrical energy which gives forward braking motion, it is termed as generator. Similarly, these two actions are performed in case motor operating in reverse direction, i.e., (reverse motoring and reverse braking actions).

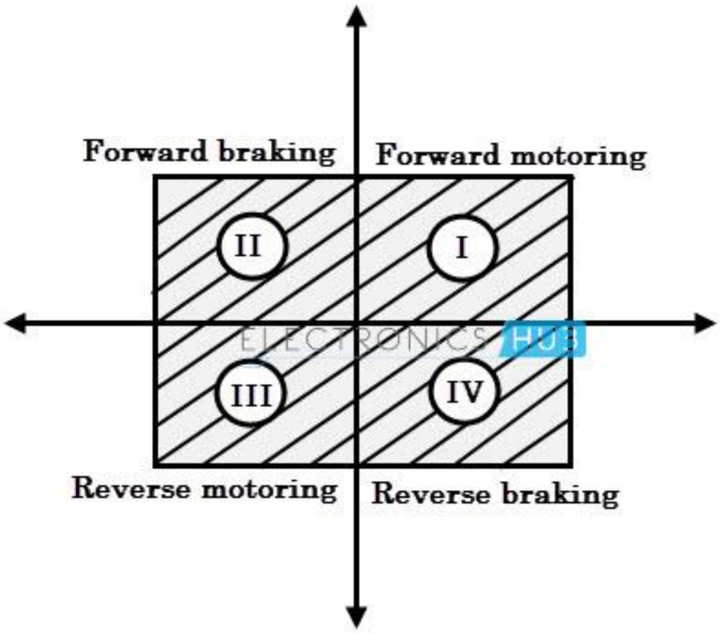

fig 5: four modes of operation

2. FOUR QUADRANT OPERATION OF A DC MOTOR

In a separately excited DC motor, the steady state speed is controlled at any desired speed by applying the appropriate magnitude of voltage, also in either direction simply by giving appropriate polarity of the voltage. The torque of the motor is directly proportional to the armature current, which in turn depends on the difference between the applied voltage V and back EMF, E,

$I = (V – E) / R$

Therefore, it is possible to develop positive or negative torque by controlling voltage, which is less than or more than the back EMF. Hence the separately excited DC motor inherently exhibit four quadrant operation. The below figure shows four quadrant operation of a separately excited DC motor in which a dot symbol on one of motor terminals indicates the sign of the torque. The machine produces a positive torque, if current flows into the dot. Similarly the torque is negative, if current flows out of the dot. Also, the relative magnitudes of voltage and back EMF are shown in figure. Figures 6-9 shows the four quadrant operation of a DC motor.

2.1 FORWARD MOTORING

In this mode of operation, the applied voltage is positive and greater than the back EMF of the motor and therefore a positive current flow into the motor. Since both current and voltage are positive, the power becomes positive. And also the speed and torque are also positive in this quadrant. Therefore the motor rotates in forward direction.

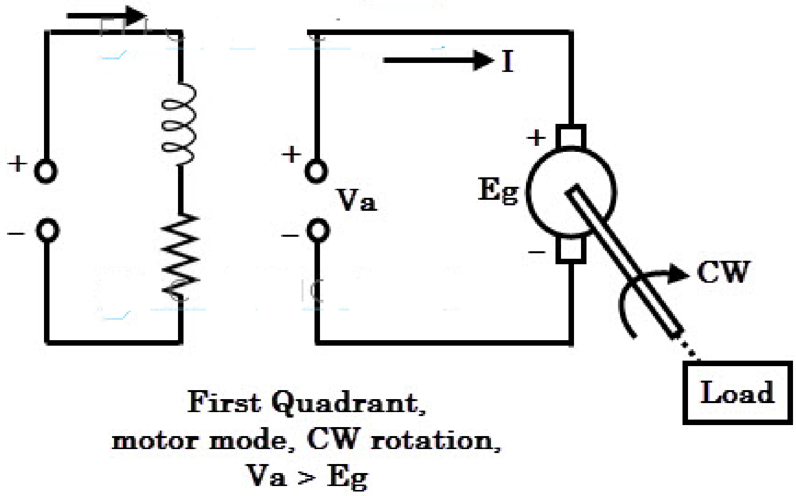

Fig 6: forward motoring

2.2 FORWARD BRAKING

In this mode of operation, the motor runs in forward direction and the induced EMF continues to be positive. But the supplied voltage is suddenly reduced to a value which is less than the back EMF. Hence the current (there by torque) will reverse direction. This negative torque reverses the direction of energy flow.

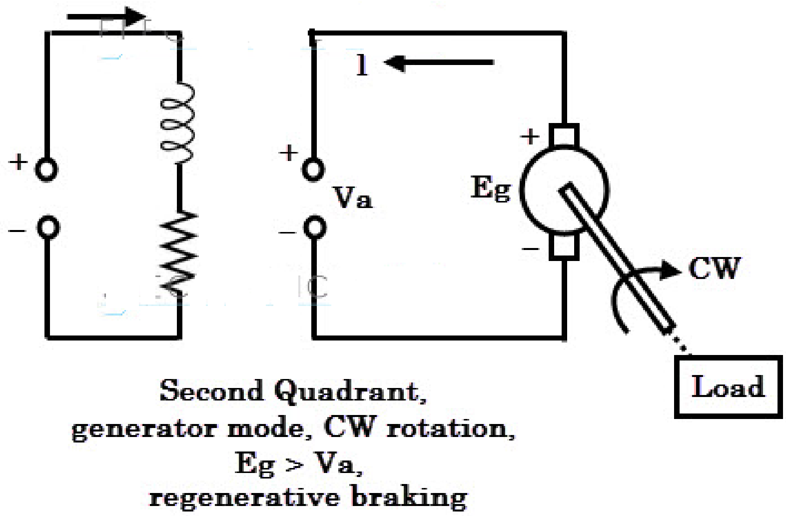

Fig 7: forward braking

Since the load torque and motor torque are in opposite direction, the combined effect will cause to reduce the speed of the motor and hence back EMF (motor EMF is directly proportional to the speed) falls again below the applied voltage value. Hence, both current and voltage become positive and the motor settle down to first quadrant again. The process by which the mechanical energy of the motor is returned to the supply is called as regenerative braking. This quadrant operation is the example of regenerative braking.

2.3 REVERSE MOTORING

This is the third quadrant operation of the motor in which both motor voltage and current are negative. Thus the power is positive, i.e., the power is supplied from source to load. Due to the reverse polarity of the supply, the motor starts rotating in a counterclockwise direction (or reverse to normal operation).

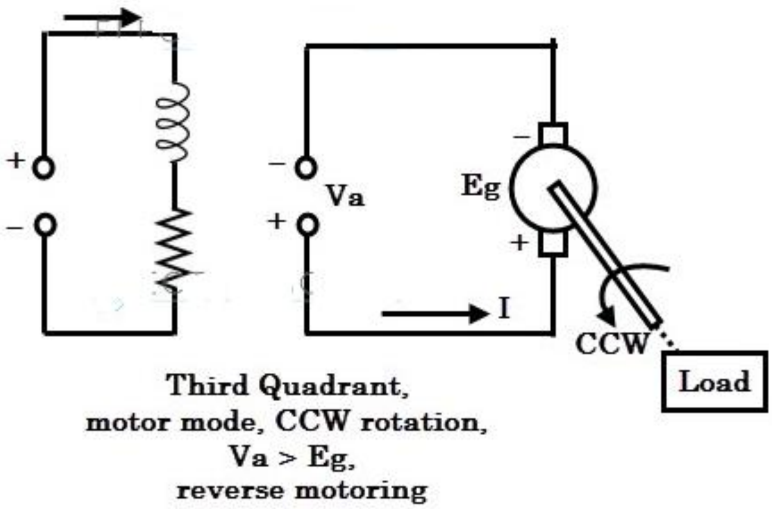

Fig 8: Reverse motoring

The operation of this quadrant is similar to the first quadrant, but only difference is the direction of rotation. The magnitude of voltage to the motor decides the appropriate speed in reverse direction.

2.4 REVERSE REGENERATIVE BRAKING

This is the quadrant-4 mode of operation in which motor voltage is still negative and its armature current is positive. This mode of operation is similar to the second quadrant operation and once again the regeneration occurs whenever the back EMF is more than the negative supply voltage. Hence the torque will be positive which opposes the load torque, thus the speed of the motor will be reduced during reverse operation of the motor. This mode of operation is mostly used for plugging in order to stop the motor rapidly. During plugging, the armature terminals are suddenly reversed, which causes the back EMF to force an armature current to flow in reverse direction. Now the effective voltage across the motor becomes 2V (as V + E_b). A braking resistor in series with the motor has to be connected to limit this current. Braking by plugging gives greater torque and more rapid stop, but the current drawn from the supply and energy stored in mechanical parts must be dissipated in resistance.

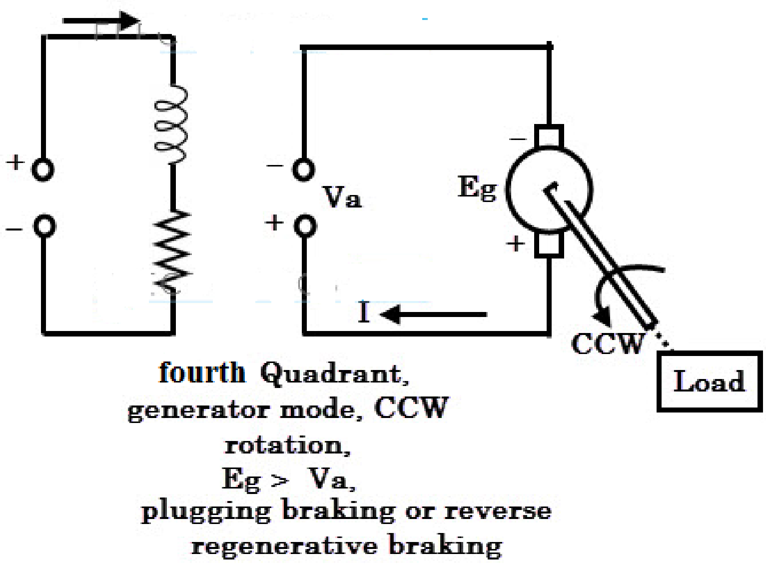

Fig 9: Reverse braking

3. APPLICATIONS OF FOUR-QUADRANT OPERATION

- Electric traction system
- Battery operated vehicles

- Lifts and cranes
- Engine test loading systems
- Spindle and tool drives in machine tools
- Auxiliary drives in robotic systems
- Position control systems

V Step Up Dc-Dc Converter

In BFEV circuit, a boost converter is required at regenerative mode. In this mode DC machine operates as a generator and generates a medium level of voltage. Then this voltage is increased up to a required level to ensure the voltage level of bi-directional DC-DC converter. Generally, this can be achieved by using a boost converter or Cuk converter

1. BOOST CONVERTER

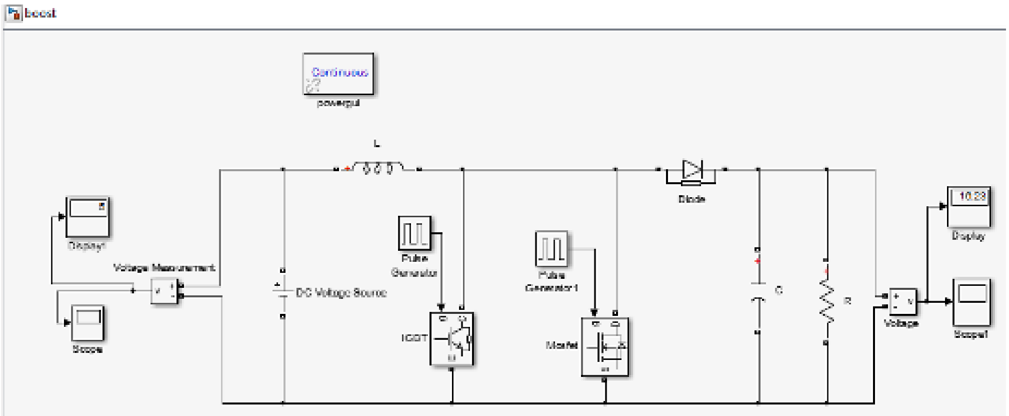

Fig 10: Boost converter simulink model

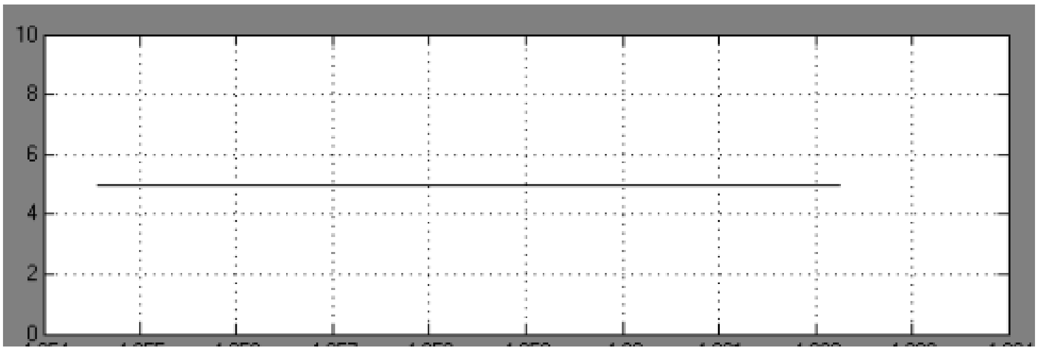

Fig 11: Input to the boost converter

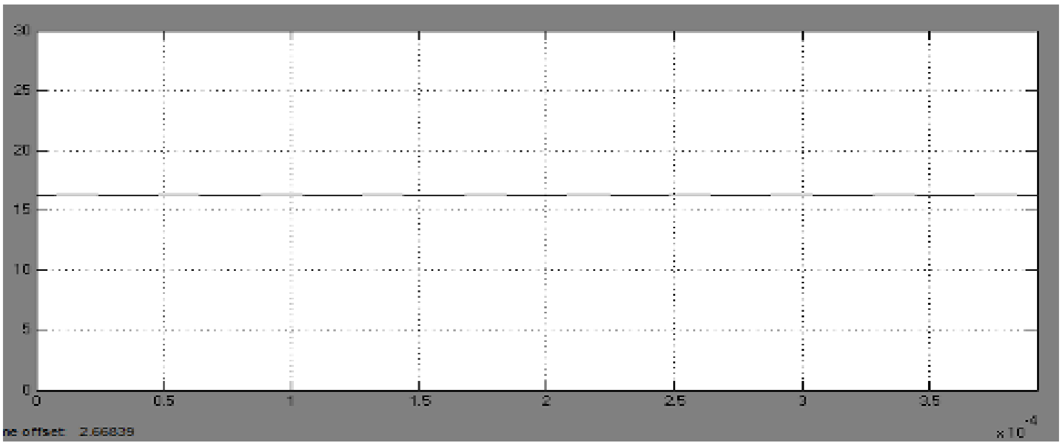

Fig 12: Output of boost converter

2. CUK CONVERTER

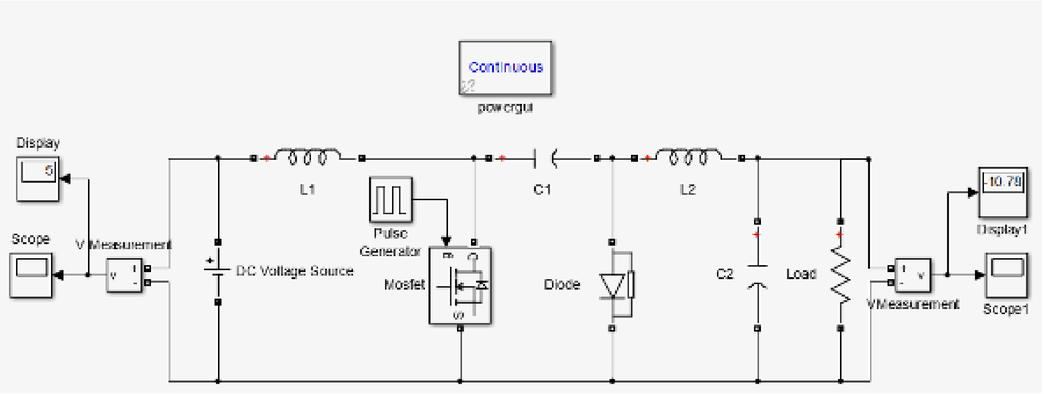

Fig 13: Cuk converter Simulink model

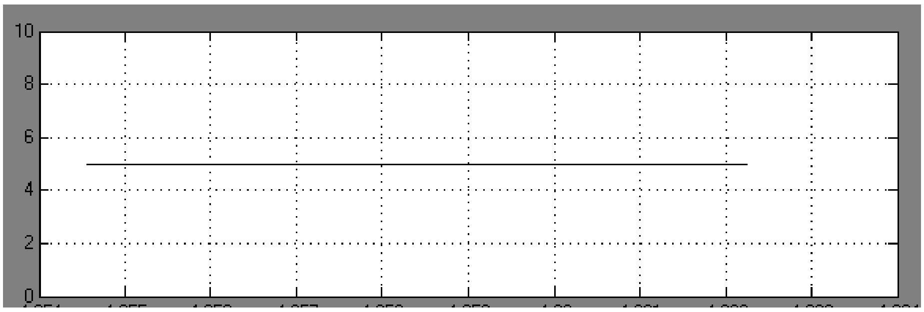

Fig 14: Input to cuk converter

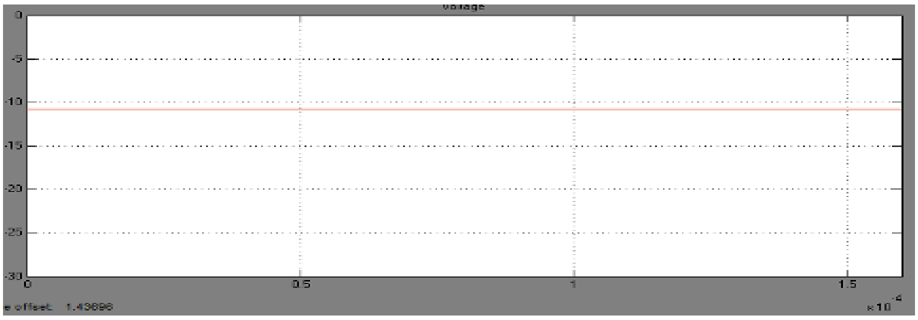

Fig 15: Output of cuk converter

3. INFERENCE

Both the cuk and boost converters were given the same input dc voltage, but we can see that the output of a boost converter contains ripples. Whereas the output of the cuk converter is ripple free and have a better output. So the cuk converter is more efficient than a boost converter in operating in conjunction with the bidirectional DC-DC converter in electric vehicle application.

VI. Hardware Implementation Of Cuk Converter

CUK CONVERTER ANALYSIS

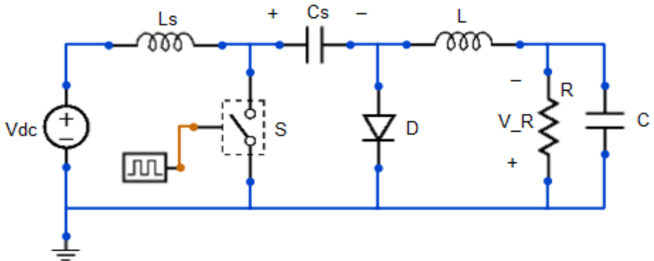

Fig 16: cuk converter

Switch OFF state:
- The inductor currents flow through the diode.
- Capacitor Cs is charged through the diode by energy from both the input and L1.
- The current IL1 decreases, because Vc1 is larger than Vd .
- Energy stored in L2 feeds output and therefore IL2 decreases

Switch ON state:
- VC1 reverse biases the diode.
- IL1 and IL2 flows through the switch.
- As VC1 > V0, C1 discharges through the switch, transferring energy to the output and L2 and therefore IL2 increases.
- The input feeds energy to L1 causing iL1 to increase.

DESIGN PARAMETERS
- *LOAD RESISTANCE* - 1K,5W
- *DUTY CYCLE* - D = Vo/(Vin+ Vo)=0.7
- *CAPACITOR SPECIFICATION* - Capacitance – 100uF,25V
- *INDUCTOR SPECIFICATIONS* - Inductance – 72mH
- *DIODE SPECIFICATIONS* - No. IN4007, Forward voltage drop = 1.1V
- *MOSFET SPECIFICATIONS*- RDS = 0.023Ω ,F = 50 KHz ,N- Channel MOSFET, P55NF06,TO-220/TO-220F, Output Voltage – 30V ,Load Current – 5A

Fig 17: Hardware setup

fig 18 : Gate pulse

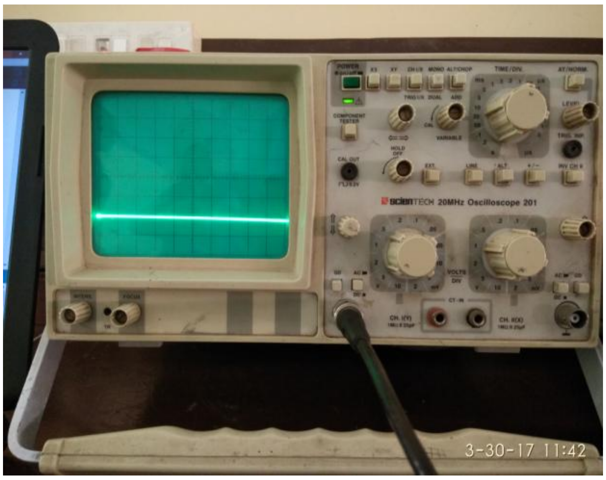

Fig 19: Output of cuk converter

VII. Electric Vehicle System

1. FOUR WHEELER VEHICLES

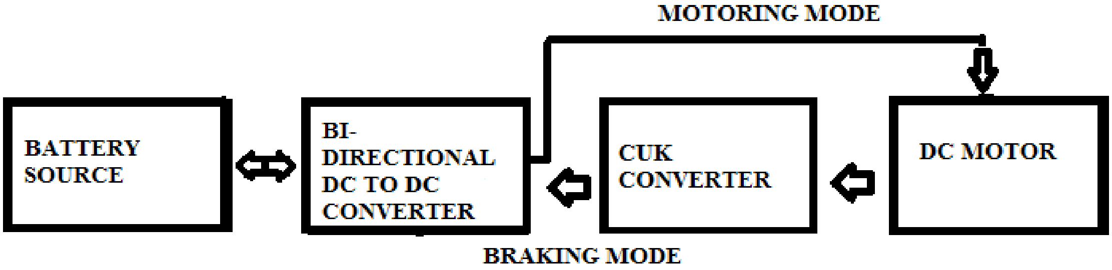

Fig 20 : Block diagram of Four wheeler system

2. SIMULATION AND RESULTS

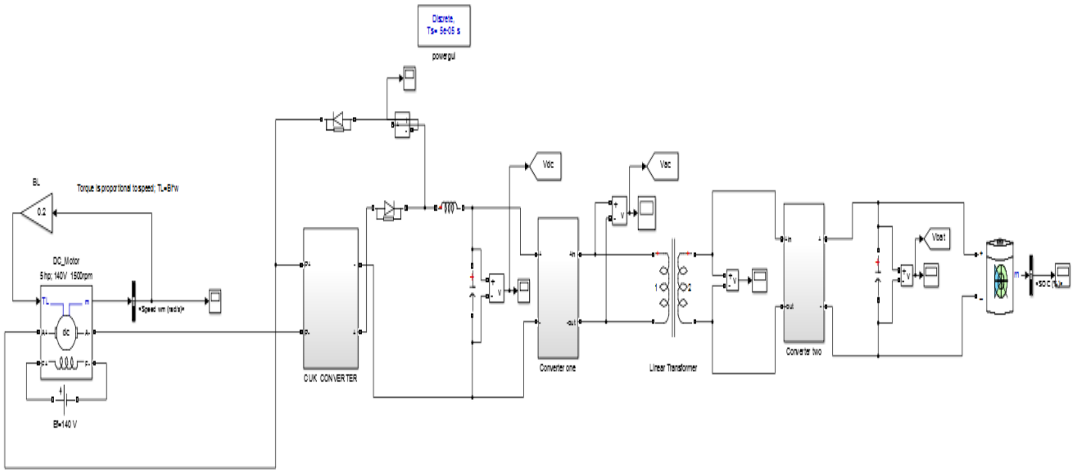

Fig 21: Simulink model of Four wheeler system in motoring mode

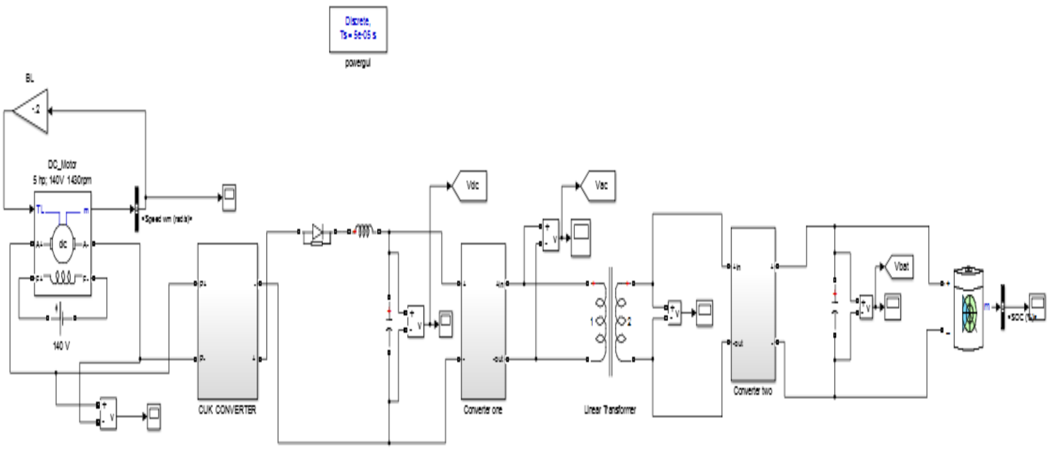

Fig 22: Simulink model of Four wheeler system in regenerative breaking mode

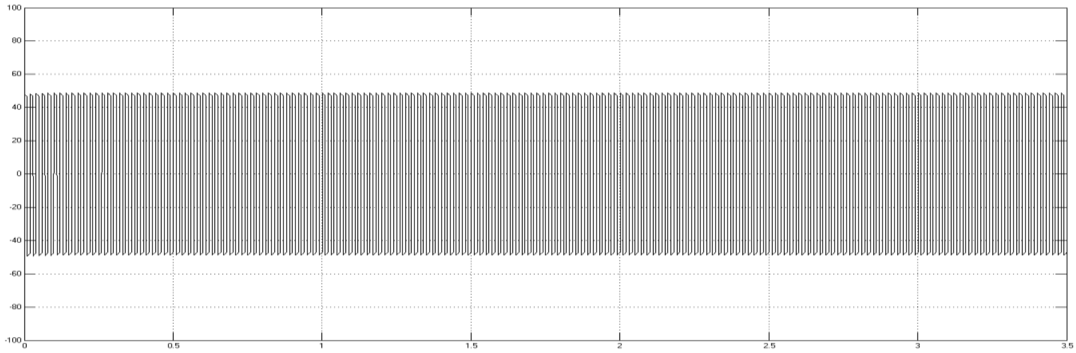

Fig 23: voltage waveform of low voltage side of bidirectional DC-DC converter

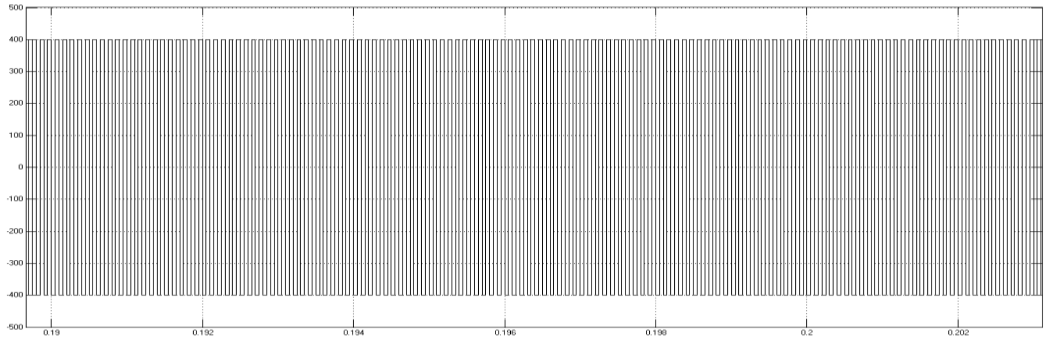

Fig 24: voltage waveform of high voltage side of bidirectional DC-DC converter

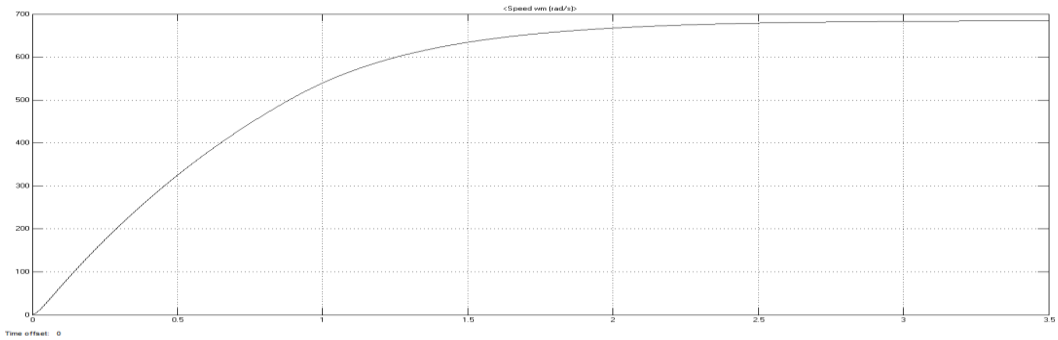

Fig 25: Speed in acceleration mode

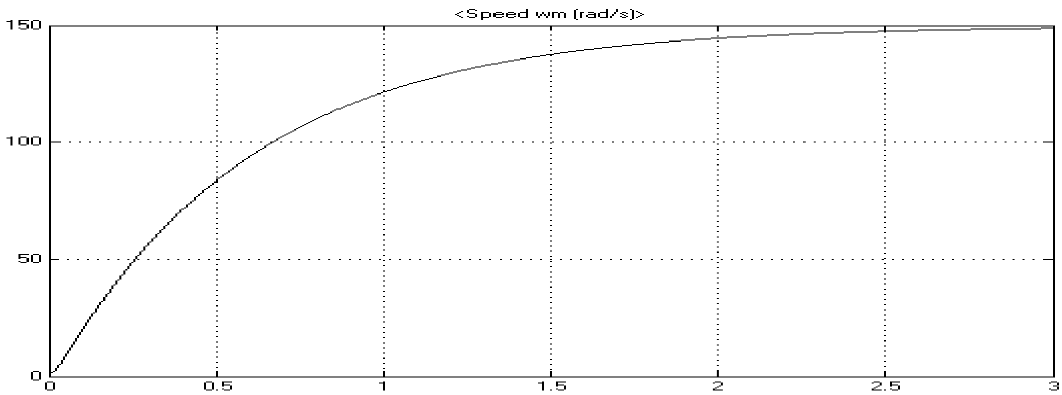

Fig 26: Speed in regenerative breaking mode

Two modes of operation: During acceleration mode, power flow is from battery to motor and during regenerative mode, kinetic energy of motor is renewed into electrical energy and fed back to battery. In four wheeler system cuk converter along with bidirectional dc to dc converter is used.

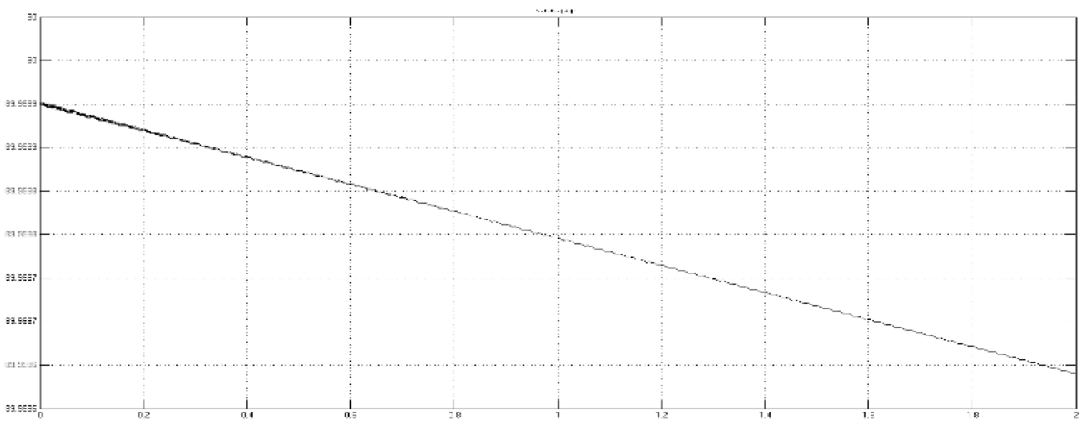

Fig 27 : Battery discharging waveform

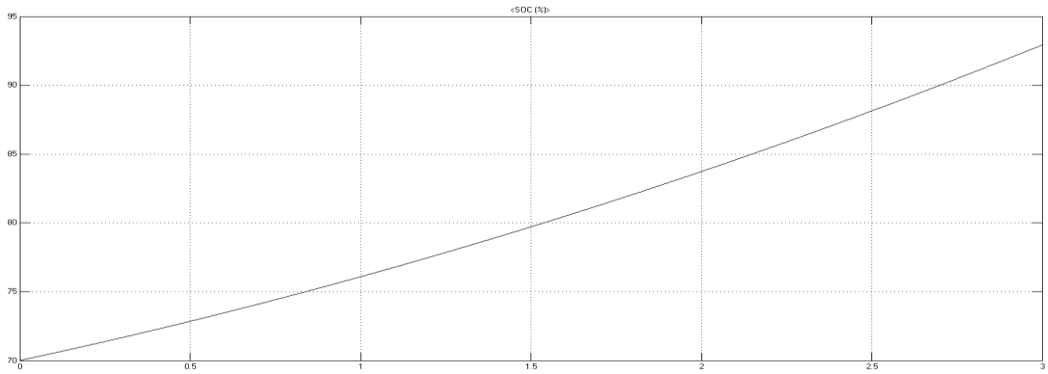

Fig 28 : Battery charging waveform in braking.

3. TWO WHEELER VEHICLES

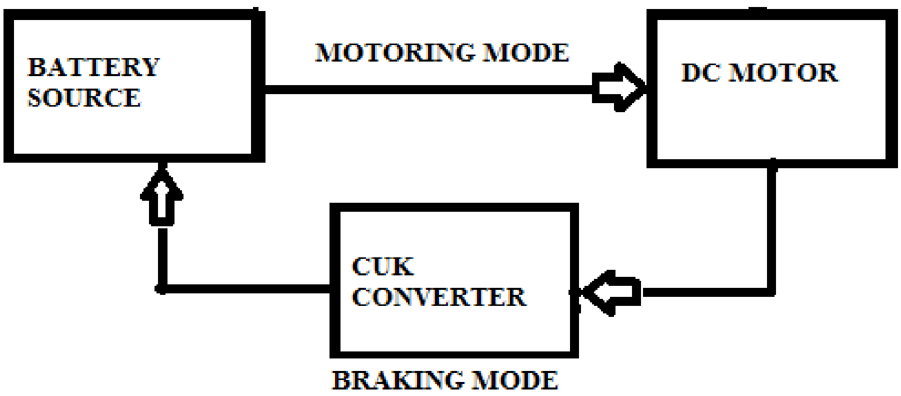

Fig 29: Block diagram of Two wheeler system

In two wheeler vehicle system the bidirectional DC-DC converter is not necessary since there is no bidirectional power flow. During motoring mode, power flow from battery to motor and during braking mode power flow reverses through cuk converter.

4. SIMULATION AND RESULTS

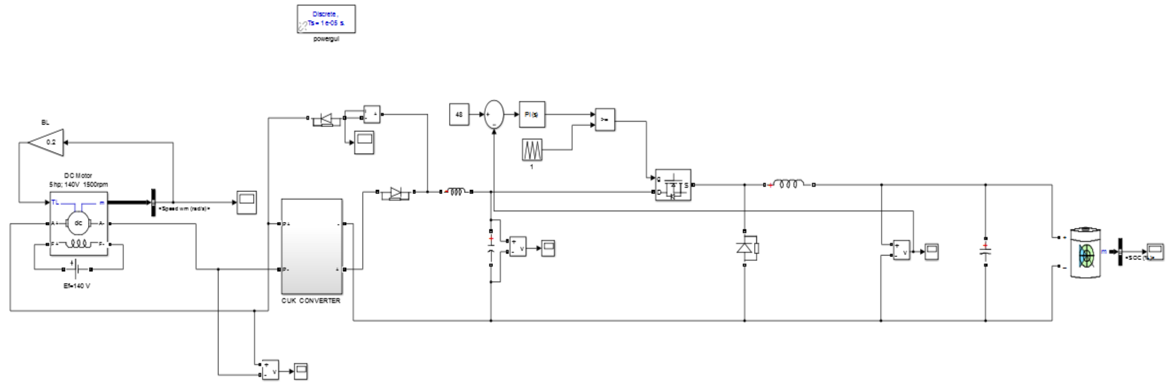

Fig 30: Simulink model of two wheeler system in motoring mode

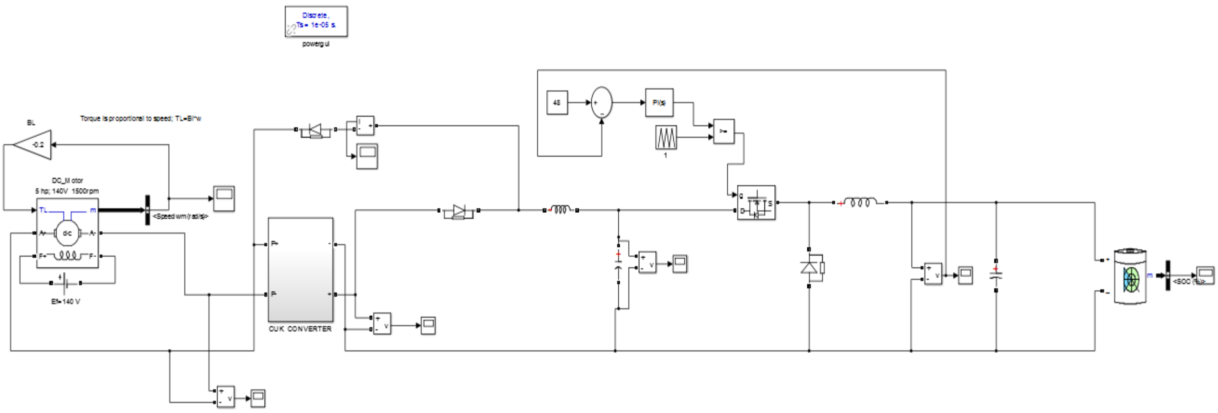

Fig 31: Simulink model of two wheeler system in regenerative braking mode

MOTORING MODE

In this mode, supply is fed to electric motor from the battery source of 48 volt.

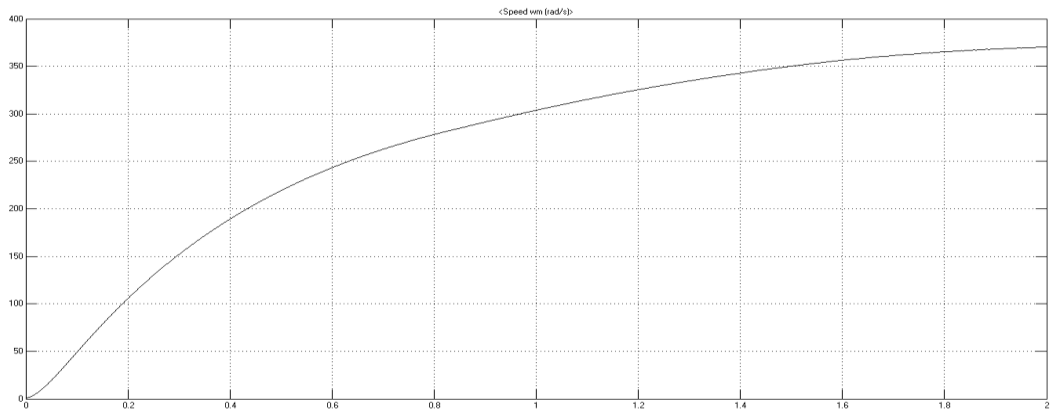

Fig 32: speed waveform

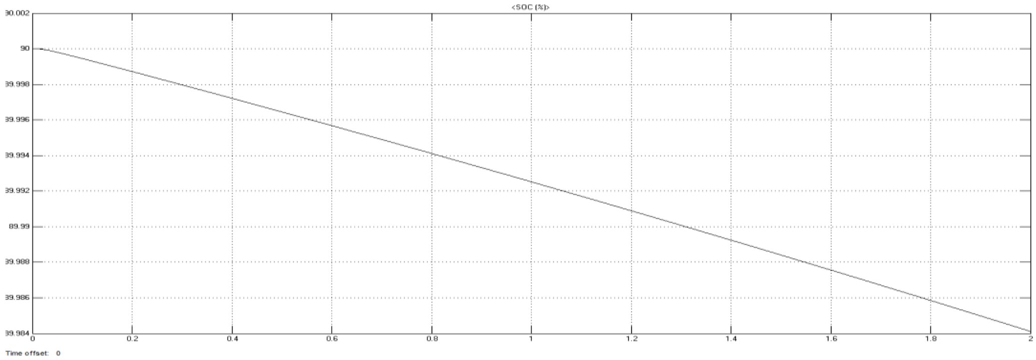

Fig 33: Battery discharging waveform

BRAKING MODE

In this mode excess energy from the motor is fed back to our battery through the cuk converter. Charging of battery during regenerative braking time from the motor. The energy wasted during braking time is effectively been reused by the model. Thus the efficiency of the electric vehicle can be improved.

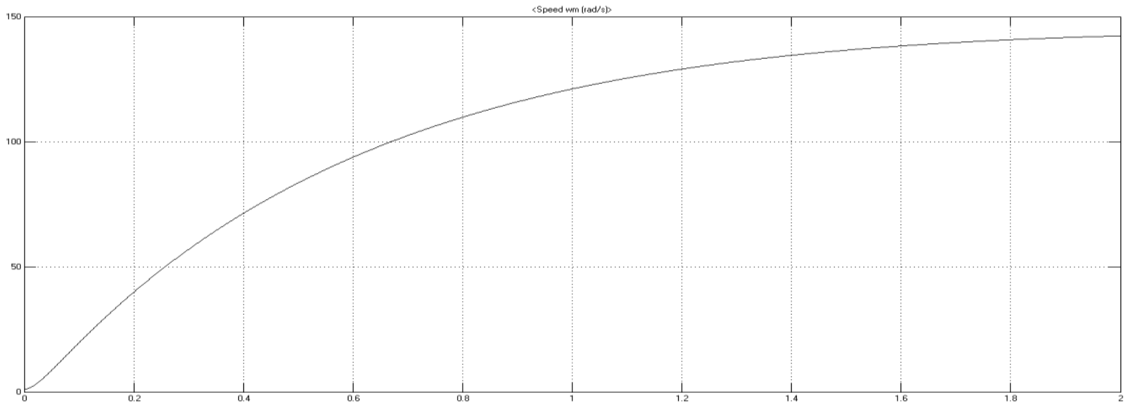

Fig 34: speed waveform

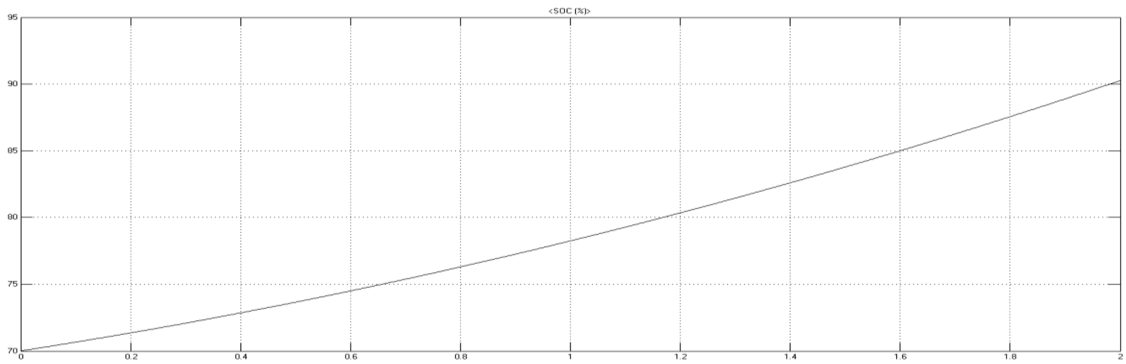

Fig 35: Battery charging waveform

IX. CONCLUSION

We have studied a battery operated electric vehicle system and it shows satisfactory performance at different driving condition. The proposed control technique with PI controller find suitable for this electric drive. The performance of the BFEV is verified under forward motoring mode, regenerative mode and when there is step change is speed command .The proposed equivalent electrical circuit for BFEV containing a cuk converter and a PI controlled bi-directional DC-DC converter offers a ripple free and stable output at both acceleration and regenerative mode as compared to the parallel switch based boost converter technique .But as the circuit become more and more complex we have formulated a new idea of using a cuk converter without a bidirectional converter and it showed a better result. The performance of dc machine can be effectively increased by using the same. This circuit does not need large capacitive filters at both sides of the converter and thus, increases the efficiency of BFEVs. As a future work, a super capacitor bank for this system can be introduced and fuzzy technique can be used for converter control instead of a pi controller. The overall cost and volume of the battery operated electric vehicle is less with the least number of components used in the system

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