OPEN ACCESS
International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-5, January 2020

DC-DC Converter used for Series-Parallel Hybrid Electric Vehicle

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Abstract*: Recently, the area of Hybrid Electric Vehicles (HEV) has seen a tremendous growth all over the world. Due to increasing levels of emissions from the conventional vehicles, rising fuel prices and environmental concerns due to global warming, entire focus of automotive industry is shifted to development of HEV's. The HEV's are classified into various configurations depending upon the degree of hybridization which include the performance of the IC engine and electric battery simultaneously for the traction purpose. The physical overview and modeling of Hybrid electric vehicle is discussed. The importance of the dc-dc converter which acts as an interface between battery and the motor drive for bi-directional power flow is proposed .In this paper, bi-directional full bridge dc-dc converter and its implementation in Series-Parallel HEV is presented .This converter topology accounts for motoring as well as regenerative braking operations.

Index Terms: - HEV, bidirectional dc-dc converter, power flow, full bridge, Series-Parallel, electric vehicle, Automotive industry

I. INTRODUCTION

The rise in pollution and effect of global warming has developed a concern all over the world. The reason for concern is the change in driving trends, increased dependency over the conventional fuels and rising fuel prices so there is a need to look for alternatives. There has been regular climate conferences all over the world including the most famous one i.e. Kyoto protocol in which serious issues relating to environmental effects due to global warming and emissions from industries and vehicles are discussed. Various rules are implemented that are to be followed by the governments for minimizing the effects by reduction in emission of harmful gases such as CO2 and other lead substitutes due to burning of fuel for vehicle propulsion. The paper discusses the current and future possible trends in the HEV industry. The main focus of this paper is to discuss the implementation of Bi-directional full bridge dc-dc converter in the Series-Parallel HEV. The operating parameters and working of its most popular converter topology is presented for forward and regenerative modes of operation. In 19th century, electric vehicles (EV) were the leaders in the market due to contributions of Edison and Tesla. But EV's could not stay longer due to its high cost and low range of driving. Therefore HEV's have been introduced in the market at the end of 19th century but have gained popularity in past 30 years due to technological advancement and its merits over conventional vehicles [1]. The HEV's combined the merits of Internal combustion engine with the electrical storage banks i.e. battery or fuel cells to overcome the limitations faced in EV's .Earlier, HEV's also faced many problems in interfacing the mechanical engine with the electrical motors only with the mechanical controls for the efficient operation. Later, lot of electrical control system was introduced for the smooth operation of these vehicles. The Hybrid Electric Vehicle technology is now replacing the traditional market at fast pace due to its high efficiency over conventional vehicles and low emissions [2].The Hybrid electric vehicle is generally provided with the two energy sources out of which one has to be electrical. There are basically two main sources of energy inflow in HEV's – one is mechanical ICE and other is electrical batteries. The advantage of adding the battery source to the vehicle is to reduce the size and capacity of the engine. The battery supplies the power to electric motor and in turn to the vehicle train during normal mode of operation at low speeds and cruising mode whereas it assists the engine power during the accelerating mode when demand of power is high. So the combination of these technologies include clubbing of high power density characteristics of ICE powered vehicles and economic factors of battery powered vehicles [3].The HEV's reduce the demand of the fuel as they are loaded with the battery banks which are a source of clean and green energy. In HEV's, battery provides electrical energy which supports the vehicle drive power and limiting the energy utilization from the engine. The power electronics circuit on board controls the power flow through engine as well as battery to maintain the efficient operation at all time. Further, HEV's does not have any external charging circuits to refuel the battery banks and it is performed while in operation. During the braking or deceleration mode, electric motor act as generator and transforms the kinetic energy of the wheels into the electrical energy which is used to recharge the battery banks. This process is known as regenerative braking i.e. charging the batteries with the power which could have lost in environment due frictional losses and heat as in conventional vehicles thus enhancing the efficiency of the vehicle [4]. To control the battery supply for forward as well as regenerative action, a power electronics interface between the battery and the motor drive is needed.

Manuscript published on January 30, 2020.
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To fill this gap, an efficient dc-dc converter is installed which boost the voltage of battery banks to the rated value of the motor drive during forward mode whereas it acts in buck mode during regenerative action when power is flowing from motor drive to recharge the battery.

To reduce the size and capacity of the battery banks, focus is to develop the dc-dc converter of high efficiency [5].Hybrid Electric vehicles are classified into three main configurations according to their architecture and working principle: - Series, Parallel and Series-Parallel [6]. The series-parallel configuration combines the models and merits of both series and parallel configurations [8]. This paper proposes a bidirectional DC-DC converter for series parallel Hybrid Electric Vehicle.

II. SERIES-PARALLEL HYBRID: -

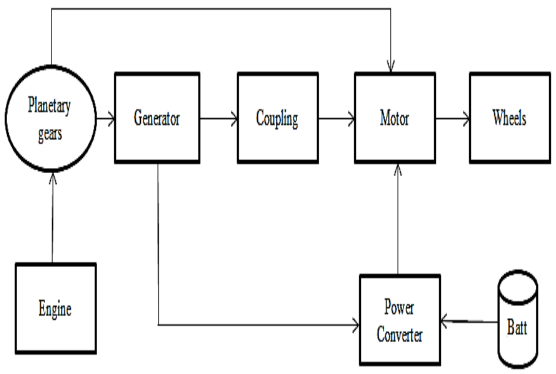

Fig. 1:Block diagram of Series-Parallel Hybrid configuration

The series-parallel architecture, the engine power is split and coupled to generator and motor through the planetary gears . The planetary gears include three component gears- Sun gear, Ring gear and Carrier gear. The Sun gear is connected to the generator, Ring gear is connected to the motor and Carrier gear is connected to the Engine shafts .The components which collaborates together and work in synchronization to form a HEV are presented here. The engine installed in HEV is quite similar to that in conventional vehicles. The size and capacity of the engine in HEV is smaller comparatively. The large size of engines make the vehicle heavier resulting in demand of additional energy during acceleration or climbing the slopes leading to depreciation in efficiency of the vehicle. In SPHEV, ICE and battery power are clubbed together to provide efficient vehicle drive operation. At low speeds or cruising mode, electric motors alone meet the demand power for a drive cycle. During acceleration, engine power and battery power are combined to satisfy the demand whereas during braking mode, engine remains idle and battery is recharging. Electric motors are the key components of HEV which are driven through battery source to assist the extra demand of power by the vehicle drive train. The motor drives even act as generator during braking mode to perform regenerative action. The kinetic energy of the wheels drives the shaft of the motor to act as a generator under the presence of permanent magnets to generate electrical energy which is used to recharge the battery. Normally, BLDC and PMSM motors find its application in HEV's due to its robust structure, compact size, high power density, control and efficiency. The speed demand is met by motor drive and is controlled by vector control technique and flux weakening methods to achieve speeds above the base speed. Electrical energy is drawn from the batteries and fed to electrical motors for forward operation whereas during regenerative action, batteries are recharged. The additional energy requirement during acceleration mode is assisted by battery source with the ICE. The reason of providing power to vehicle by ICE at high loads is due to high cost of the battery banks. The batteries should be light and compact and highly efficient to provide more power output. The shafts of engine, motor and generator are mechanically coupled to each other. The planetary gear ratio decides the flow of power from engine to motor drive and generator drive. During acceleration mode, more power will be transferred to motor to achieve the power demanded by the vehicle train. Three main components of epicyclic gears are explained as follows: -

Sun gear- the central gear,

Carrier gear- holds one or more planet gear clubbed with sun gear,

Ring gear- outer gear with its teeth facing inwards and clubbed with the planet as well as sun gear.

The gear ratio of the planetary gears denoted by K is given by equation: -

$$N_S w_S + N_r w_r = (N_s + N_r) w_C \qquad (1)$$

where, w_r, w_c and $w_s$are the angular velocities of ring, carrier, planet and sun gears, and N_r, N_c and N_s are the number of teeth of ring, carrier, planet and sun gears.

Final expression is given by the equation: -

$$-\frac{N_r}{N_s} = \frac{w_S - w_C}{w_r - w_C} = -K \qquad (2)$$

The power shared by the engine, battery, generator and the motor are given by the mechanical and electrical power laws. Following equations for these laws must satisfy the zero condition in order to verify the energy law.

Mechanical power law: -

$$P_{sun} + P_{carrier} + P_{ring} = 0 \qquad (3)$$

III. ENERGY MANAGEMENT SYSTEM

This system deals with the control and management of hybrid electric vehicle. It is called as the control center of the vehicle model. The EMS is responsible for sending the signals to all other blocks for working in synchronization with each other. The accelerator pedal is connected with the EMS through which its input is processed and accordingly signal is sent to battery to engine for vehicle propulsion. The system also controls the amount of power required by the drive cycle to be shared between battery and engine which is further controlled through Battery Management System. Energy Management System is classified as follows: -

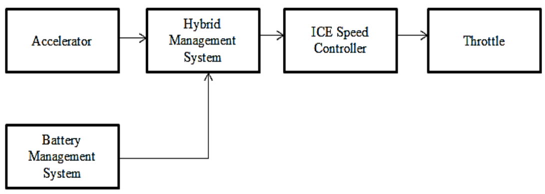

Fig. 2: Energy Management System Battery management system:-

Battery Management System is a part of EMS which controls the charging and discharging of battery according to the required drive cycle. Parameters including voltage, current and SOC of the battery is evaluated in battery management system. The voltage and current of the battery decides the output power of the battery which is utilized to operate the motor drive. State of charge of battery is the key parameter which is managed in BMS and further decides the operation of battery for a particular drive cycle. The State of charge of battery depicts the percentage of charge or current left in battery at a particular interval. The SOC of the battery is maintained at minimum of 20% so that sedimentation of battery is avoided. The BMS controls the SOC of the battery between the safety limits and sends the signal to Hybrid management system for specific operation.

Power of the battery is given by: -

$$P_{batt} = V_{oc}.I_{batt} - I_{batt}^2.R_{batt} \quad (4)$$

where V_{oc} = open circuit voltage

I_{batt} = internal battery current

R_{batt} = internal resistance of the battery

The state of charge (SOC) of the battery is given by: -

$$SOC = \frac{I_{batt}}{Q_{max}} \quad (5)$$

Where Q_{max} = capacity of the battery in terms of Ah

ICE Speed Controller:-

The generator speed is taken as a feedback from the generator shaft and fed to this system. The ICE speed and power as explained before is also fed into this system. The shafts of ICE and generator are coupled to each other. This system becomes active only when Hybrid management system sends the Hybrid ON signal to it. After enabling the Hybrid signals the engine and generator becomes operative else only battery will supply the power to the motor drive. The clubbed power of generator and engine is delivered to motor drive depending upon the speed and torque demanded from the closed loop cycle of required drive power. This system uses the PI controller so that demand engine speed to produce the adequate power by the system matches its actual speed. The throttle signal is generated at the output of PI controller for vehicle propulsion.

IV. MATHEMATICAL MODELING OF HEV

The performance of HEV depends upon various frictional forces acting on it which varies with the shape and design of the vehicle. These forces are presented with the help of equations as:

Rolling frictional force: - It acts due to friction between the tires of the vehicle and the road surface. It is computed by the equation: -

$$F_{rr} = \mu_{rr}\, mg \quad (6)$$

Where μ_{rr} is the rolling resistance

Aerodynamic drag: - It comes into force due to drag applied to the vehicle body by the opposing wind flow. It is given by the equation: -

$$F_{ad} = ½\, \rho A C_d v^2 \quad (7)$$

Where ρ is the air density

C_d is the drag coefficient

A is the frontal area

Acceleration force: - It comes into play when vehicle is accelerating and is given by equation: -

$$F_{la} = m\frac{dv}{dt} = ma \quad (8)$$

Angular Friction is given by equation which appears across the rotating parts including tires and hubs.

$$F_{wa} = \frac{IaG^2}{r^2} = \frac{1}{2}mw^2\frac{aG^2}{r^2} \quad (9)$$

where G is the gear ratio and I is the moment of inertia

Total Tractive force: -

$$F_t = F_{rr} + F_{ad} + F_{la} + F_{wa} \quad (10)$$

$$F_t = \mu_{rr}\, mg + 0.625AC_d v^2 + ma + \frac{IaG^2}{r^2} \quad (11)$$

Torque: -

Torque referred to shaft of motor is given as: -

$$T_m = F_t.r \quad (12)$$

Where r is the radius of the tire

Energy: -

Energy output at the axle to accelerate the vehicle: -

$$E_a = F_a.Distance \quad (13)$$

The power developed by the vehicle which further is shared by engine, generator, motor and battery is given by the equation: -

Power developed by motor:-

$$P_d = w.T_m \quad (14)$$

where w is the speed of motor and T_m is the motor Torque

PROPOSED DC-DC CONVERTER

The proposed configuration of Bi-directional converter is shown in Fig.3 which is an isolated coupling of two full bridge circuits through transformer. The converter is used for buck–boost operation .Bidirectional dc-dc converters find its application in charging and discharging circuits for batteries. From the Fig.3, it is clear that the circuit to the left of the isolation transformer is current fed bridge due to presence of source inductance whereas the circuit to the right side is voltage fed bridge. In the circuit, the left hand side circuit depicts battery side and right side is high voltage motor side. The transformer is inserted to isolate the battery and motor side having turns ratio n:1. The source inductance L_s acts as a booster in case power flows from source to load

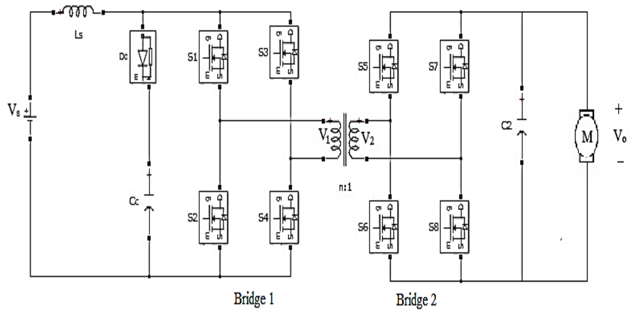

Fig. 3:Bi-directional full bridge dc-dc converter

Moreover the same inductor starts acting as an output filter when power flows reverse i.e. from high voltage side to low voltage side during buck operation. The clamp branch having capacitor and diode in series is connected in parallel to the input leg of bridge 1. It is to reduce the difference of currents due to source inductor and leakage inductor of the isolation transformer. The primary role of transformer is to provide isolation .Moreover the leakage inductance of an isolation transformer acts as an energy storing element. Duty cycle for inverter is 50%.

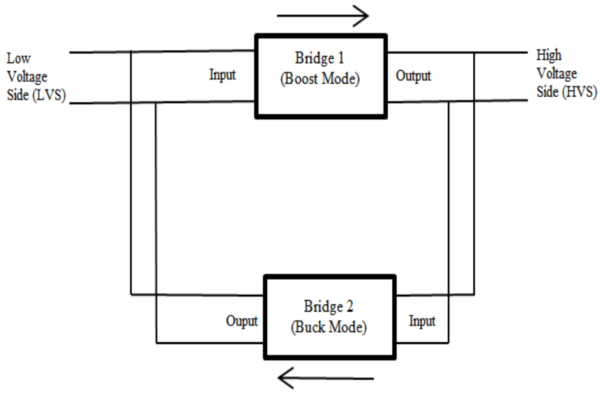

Fig. 4: Direction of power flow

From Fig...3 , turns ratio of transformer is denoted by 'n'

Where n = (V_1/V_2) (15)

V_1 = voltage across the primary winding of transformer

V_2 = voltage across the secondary winding of transformer

During the Boost operation or forward mode, power flow takes place from battery to motor. The Bridge 1 at the low voltage side containing switches S1-S4 is active during this mode and it act as inverter which supplies the alternating voltage V_1 of high frequency, given by f = ($1/T_s$) across the input of the isolation transformer i.e. its primary winding with the duty ratio(0.5). The role of isolation transformer is to transform the alternating voltage according to applied turn ratio n i.e. V_2 = (V_1/n). The output alternating voltage across the secondary of the transformer is fed to the Bridge 2 at motor side acting as rectifier. During single pulse width modulation, only one pulse appears for one half cycle and the output rms voltage depends on variation in width of the pulse. The gating pulse for the switches are generated by comparing the reference fixed dc voltage of magnitude $V_s$with the triangular wave of magnitude V_{carr}.The frequency of the signal defines the fundamental frequency of the ac output voltage as shown in Fig.5.

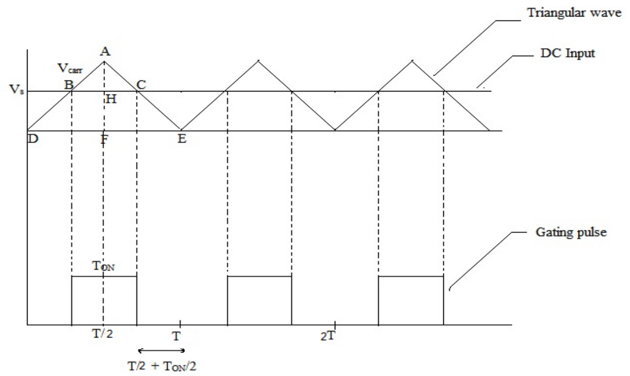

Fig. 5: Single pulse width modulation technique

The modulation index is given by: -

$$m_f = \frac{V_s}{V_{carr}} \quad (16)$$

From the Fig..7, by the principle of congruency of two triangles,

$$\triangle ABC \cong \triangle ADE \quad (17)$$

$$\frac{V_{carr}}{V_{carr} - V_s} = \frac{AF}{AH} = \frac{DE}{BC} = \frac{T}{T_{ON}} \quad (18)$$

$$D = 1 - M \quad (19)$$

The rms value of the output voltage can be given by the equations: -

$$V_1 = \left\{ \frac{1}{T} \int_{\left(\frac{T}{2} - \frac{T_{ON}}{2}\right)}^{\left(\frac{T}{2} + \frac{T_{ON}}{2}\right)} V_s^2 \, dt \right\}^{1/2} \quad (20)$$

$$V_1 = Vs\sqrt{\frac{T_{ON}}{T}} \quad (21)$$

$$V_1 = V_s\sqrt{D} \quad (22)$$

Isolation transformer boosts the ac voltage depending upon the turn's ratio given by the equation: -

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = n \quad (23)$$

$$V_2 = \frac{V_1}{n} = \frac{V_s}{n} \quad (24)$$

The boosted voltage is fed to the input of the rectifier bridge and its rms value is given by the following equations: -

$$V_p = \sqrt{2}V_2 \quad (25)$$

Where V_p is the peak voltage of V_2

Average output voltage of rectifier is given by: -

$$V_o = \frac{2V_p}{\Pi} \quad (26)$$

Similarly, in Buck operation, power flow reverses from motor to battery. The Bridge 2 at the high voltage side consisting of switches S5-S8 is active and act as inverter whereas Bridge 1 acts as a Rectifier.

V. SIMULATION RESULTS AND DISCUSSION

Series-Parallel Hybrid Electric Vehicle is simulated using bi-directional full bridge dc-dc converter. Various characteristics including power, voltage, current and SOC of the battery are analyzed. The simulation is carried out in MATLAB environment for the following drive cycle: -

Acceleration period (Time: 0-2 sec)

Constant period (Time: 2-6 sec)

Deceleration period (Time: 6-8 sec)

The parameters used for simulation are presented in Table.1

Table.1 Simulation parameters

Parameters	Specifications
Input voltage	120 V
Transformer Turns ratio	100/486
Switching Frequency	20 kHz
Duty ratio	0.5
Mass of vehicle	800 kG
Displacement	1200 cc
Vehicle Power	36 HP, 1700 rpm
Radius of tire	0.3 m
Drag coefficient	0.26
Sun speed	-226 rad/s
Ring speed	195 rad/s
Planet speed	460 rad/s

Carrier speed	78.5rad/s
Number of teeth in sun gear	18
Number of teeth in ring gear	48
Number of teeth in planet gear	15
Planetary gear ratio	2.61
Frontal Area	2.57 m^2
Moment of Inertia	0.5 Kgm^2
Vehicle velocity	52 Km/h
Acceleration angle	26.4^0
Deceleration angle	-26.4^0
Distance travelled	88 m in 8 sec
Rolling frictional force	39.19 N
Angular force	193.149 N
Total Tractive Force	232.339
Average Torque for Drive Cycle	70 Nm
Average Power for drive cycle	13.95 kW
Motor	25 kW, 600V, 8 pole PMSM, 6000 rpm
Generator	10 kW,600V, 2 pole PMSM, 2000 rpm
Battery	15 KW, 120V, 6.5Ah Nickel meta-hydride
Engine	20 KW, 1700 rpm

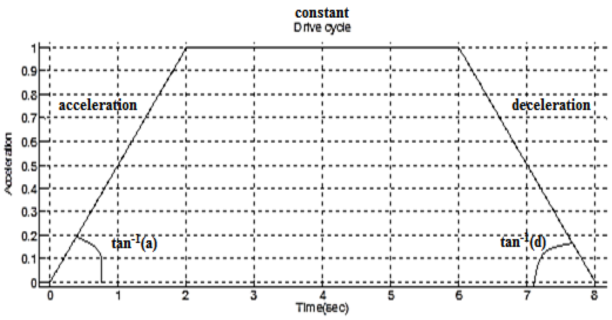

Fig. 6: Drive cycle for the HEV

Fig.6 represents drive cycle consisting of acceleration constant and deceleration modes of operation .$\tan^{-1}$(a) and $\tan^{-1}$(d) are accelerating and decelerating angles respectively.

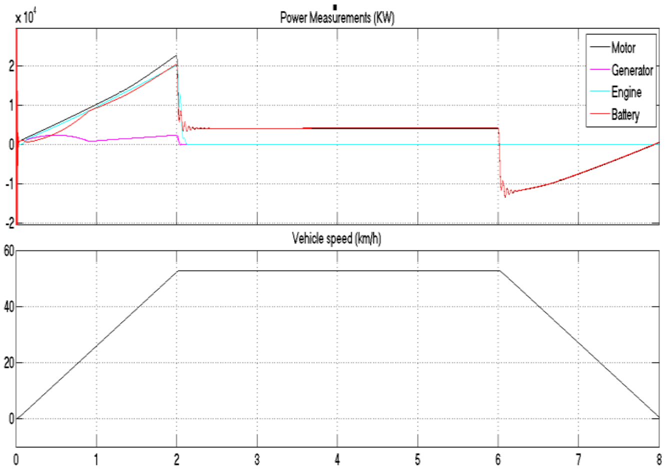

Fig. 7: (a) Power flow waveforms (b) Vehicle speed

The Fig.7 (a) depicts the power measurements of motor, generator, engine and battery for a given drive cycle in acceleration, constant and deceleration periods. And the Fig.7 (b) depicts the change in velocity of the vehicle for the entire cycle. In acceleration mode, engine, motor, generator and battery are supplying power combined with each other. During constant operation, only battery supplies the power whereas engine and generator are idle. During deceleration mode, regenerative action takes place and negative battery current indicates the charging mode.

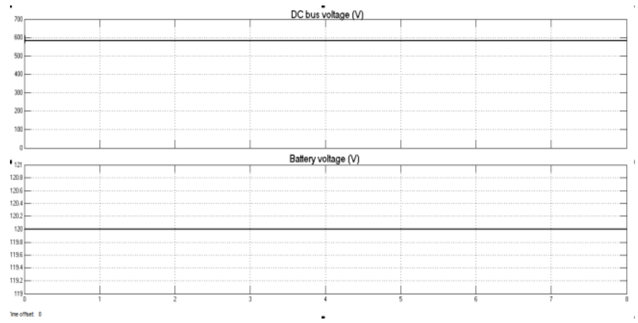

Fig. 8: (a) DC bus voltage (b) Battery voltage

The Fig.8 (a) depicts the boosted output dc voltage obtained from the bidirectional dc-dc converter. Whereas Fig.8 (b) shows the input voltage of converter.

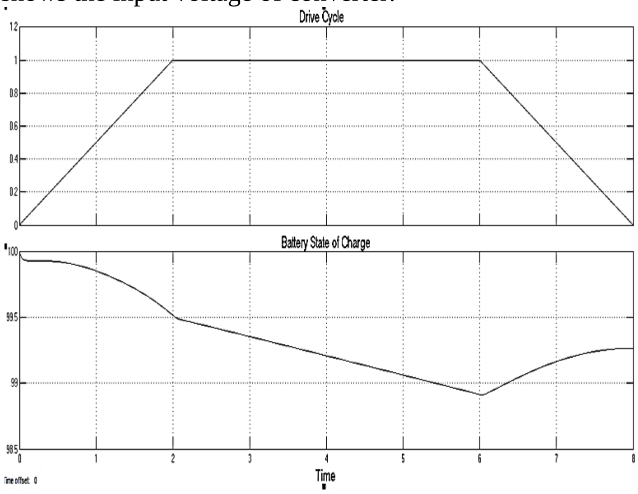

Fig. 9: (a) Drive cycle (b) Battery SOC

The Fig..9 (a) shows the drive cycle given to the HEV for different modes. 9 (b) shows change in SOC of battery with respect to drive cycle.

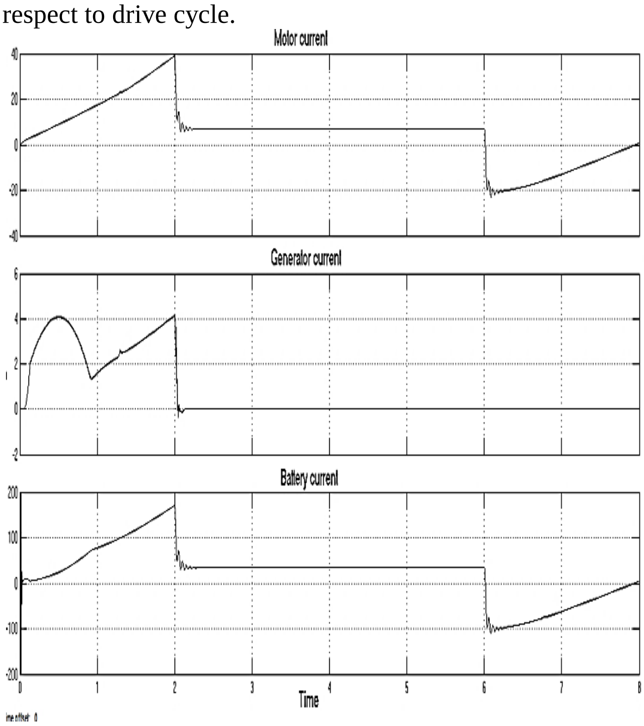

Fig. 10: Current waveforms

The Fig..10 shows the input motor, generator and the battery's currents varying with the drive cycle. During regenerative action, motor acts as a generator as recorded current direction is reversed. In this mode battery is charging.

VI. CONCLUSION

The paper presents a comprehensive analysis of HEV along with implementation of a suitable Bi-directional in series-parallel hybrid electric vehicle. The driving characteristics including power, voltage, current and SOC characteristics of battery are presented. The bi-directional converter allows the flow of power from battery to motor during forward acceleration mode and vice-versa during braking mode. A suitable switching technique is employed for bi-directional power flow to achieve efficient, economical, reduced battery size and increased driving range of HEV.

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