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Design and Simulation of Multi Input Converter for Hybrid Vehicle Applications

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ABSTRACT: Hybrid vehicle improves efficiency of the conventional vehicle and also act as range extender for battery vehicles. A hybrid vehicle consists of two sources namely generator and battery. Generator is run by Internal Combustion Engine. Series hybrid vehicle consists of a motor that drives the wheel and the motor is powered by combination of generator and battery power. Power management between battery and generator requires design of a converter that helps in battery charging/discharging according to the required condition. The converter should have good transient behaviour so that vehicle reaches maximum speed in less time, should be able to charge the battery during re-generation action of the motor and should also provide isolation, so that equipments do not get damaged under faulty conditions In this paper, such configuration is presented along with simulation results. The system was simulated in MATLAB in closed loop and found that DC-DC converter is able to achieve power management. After verification of the simulation, selection of components for hardware is done and PCB design is made based on the selected components. Application of this DC-DC converter is to operate the vehicle in proper power modes while vehicle is running and also act as voltage controller during charging of battery when vehicle is connected to grid.

KEYWORDS: DC-DC Converter with isolation, BLDC Generator, Series Hybrid configuration, Regeneration, Transformer design

I. INTRODUCTION

Since fossil fuel is fast depleting, there arises a necessity to reduce the consumption of it. The present conventional vehicles have fuel efficiencies very less and it is highly polluting the environment. Because of lower efficiency, carbon deposits are more in the engine which makes it more difficult in maintaining it. Though number of attempts is made to improve efficiency of the conventional vehicles, there is not much improvement in the efficiency. To overcome these problems, hybrid vehicles are proposed, where the fuel consumption is kept at maximum efficiency and rest of the power is compensated from other sources such as battery, fuel cell etc. There are various Configurations available in hybrid technology such as parallel hybrid, series hybrid, combination of series and parallel, but series hybrid vehicles are preferred for following advantages [1].

a) Transmission is not required
b) Gearless travel is possible
c) Motor itself can act as brakes, so exclusive brakes are not required
d) Electric motors have high power to weight ratio, hence Electric motors are of lesser size when compared to conventional engines of same power
e) Higher starting torque for electric motors when compared to conventional engines, hence maximum speed can be attained in fewer seconds
f) Generator is always kept at maximum efficiency

   Important criteria for series hybrid vehicle are to choose proper Powertrain, so that vehicle has maximum efficiency and minimum complexity. It should not affect the performance of the vehicle, such as speed and torque [2]. There are various topologies possible such as

   a) Semi-Active
   b) Series-Active
   c) Parallel-Active

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In a Semi-Active hybrid, a dc–dc converter is employed, in addition to the battery and generator. There are two possible semi active configurations such as battery active and generator active. In the capacitor semi active configuration, the dc–dc converter is placed between the capacitor and dc link. In battery semi-active configuration, converter is placed between battery and DC link.
In a Series-Active Hybrid topology is an enhancement of the battery semi active hybrid, it solves the problems of generator voltage variation and matching by placing an additional dc–dc converter between the generator and the dc link. The main disadvantages of the topology are the addition of a full rating dc–dc converter and reduced efficiency, since there are two conversion stages between the battery and the dc link.
Parallel Active Hybrid topology is, by far, the optimal active hybrid, reported in literature. It solves the problems of generator voltage variations and matching by placing a dc–dc converter between the generator and the dc link. In addition, it allows a nearly constant current flow from the battery as well as voltage mismatch between the battery and the dc link by placing a dc–dc converter between the battery and the dc link. The main disadvantage of the topology is the utilization of two dc–dc converters, one rated at the load average power and another rated according to the dynamic peak power, bringing complexity, control effort, and additional losses into the system.

II. CHOOSING A DC-DC CONVERTER

The motor which is used in the vehicle may be of different types such as BLDC, PMSIM, Induction motor etc [3]. Based on the motor type, generator type is to be chosen, so that efficiency of the system is not affected. The generator is run by using the conventional piston based engine run by petrol or diesel.

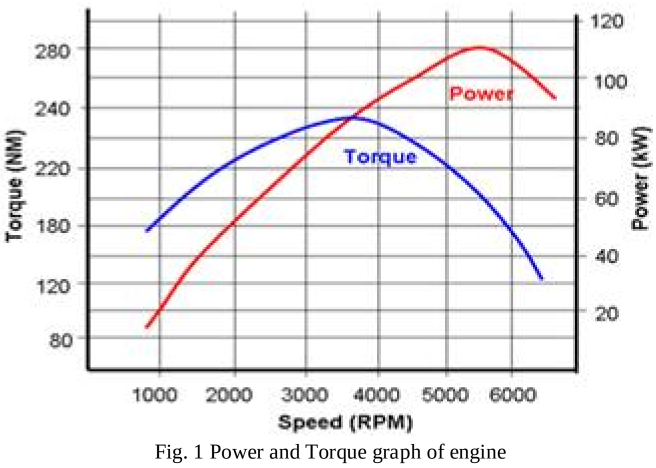

Fig. 1 Power and Torque graph of engine

Fig. 1 explains the efficiency of the engine based on the Torque and RPM of the engine. It is seen that a point exists where the engine has maximum power. The point where the engine has maximum efficiency has a fixed torque and RPM related to it. At this point, the engine would spend only less fuel; hence this point is most preferred. This point is fixed for the engine that runs the generator, so that the engine has maximum efficiency, spends less fuel. By fixing this point, the generator would produce only fixed amount of power. Based on this power, required power of motor is adjusted by using the battery, hence power electronics plays important role in splitting the power between the sources. Fig. 2 shows the basic blocks of series hybrid vehicle. The fuel runs the engine, where it is connected to the alternator [4]. The battery supports the power requirement of the motor. The following conditions are met by the power electronics part of the system

a) If generator power is more than motor power, battery is charged
b) If generator power is less than the motor power, battery is discharged

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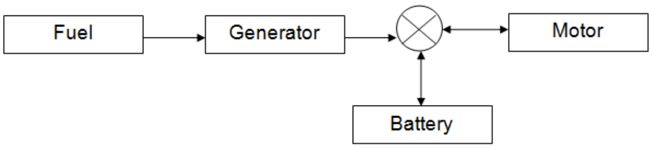
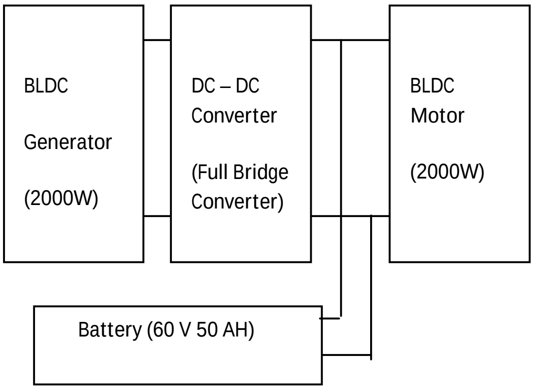


Fig. 2 Basic Block Diagram of Series Hybrid vehicle indicating power flow among the blocks

When the motor is in acceleration mode, more power is required by the motor, hence battery would support the power required. Hence the battery is in situation of supporting huge power in short span, so that quick response is seen between the acceleration applied and speed is seen by the driver.

Proper controller design has to be done, so that energy management of the complete system happens.

Before proposing closed loop operation of the device, it is better to have better understanding of choosing a proper DC-DC Converter [5]. The following configurations are chosen for further studies



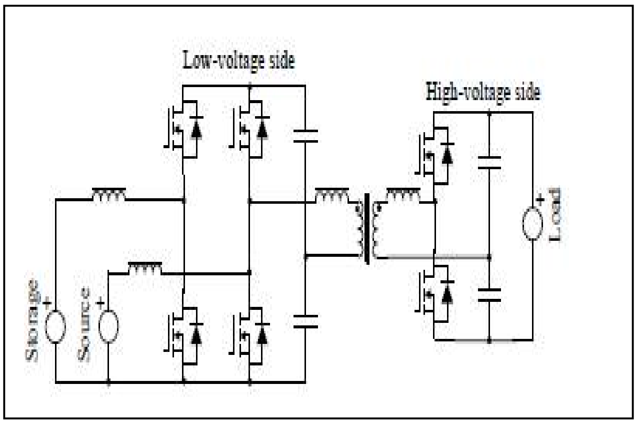
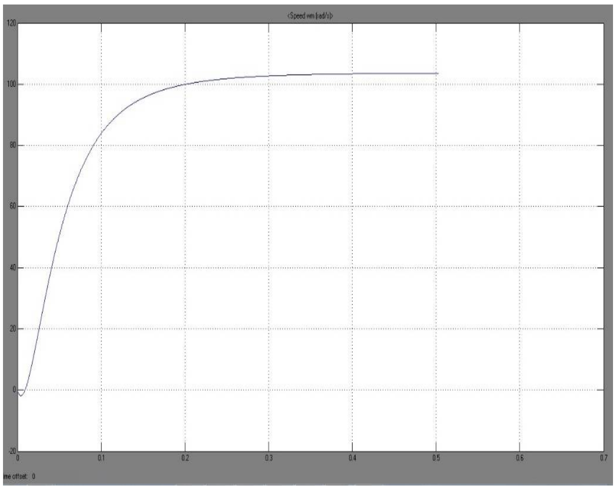
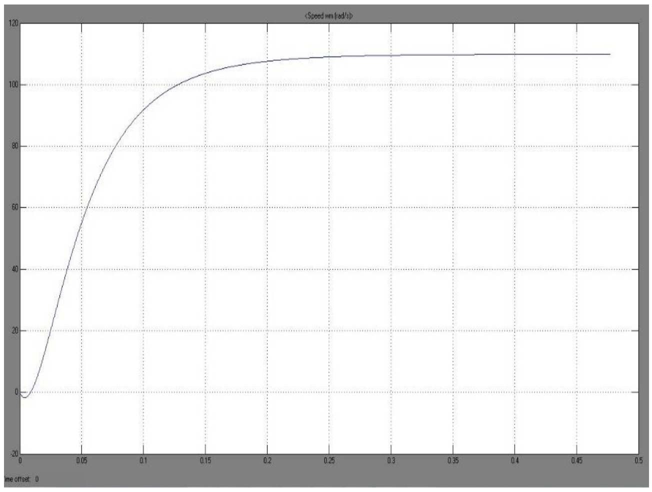


Fig. 4 System with Single Input DC-DC Converter (Topology2)

Fig.3 Multi Input Multi Output DC-DC Converter(Topolgy 1)

The two topologies are connected to a DC motor in MATLAB and analysed. The speed of the motor is plotted against time.





X-Axis: Time in s
Y–Axis: Speed in Rad/s
Fig. 5 & 6 Time vs. Speed of Motor with Topology 1 & 2

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Fig 5 and Fig 6 shows the graph between time and speed of motor. In fig 5, it is seen that the motor achieves maximum speed in 4 sec whereas in Fig. 6, it shows that the speed of motor achieves maximum speed in 3 sec. Hence topology 2 (with battery having no electronic switch) has best performance, because it supports good transient behavior. The DC bus voltage is controlled, so that power flow of the battery can be controlled. The following conditions are followed

a) If DC bus voltage is more than battery voltage, battery would get charged.
b) If DC bus voltage is less than battery voltage, battery would get discharged.

The DC bus voltage can be controlled using the DC converter.

III. CLOSED LOOP OPERATION OF HYBRID VEHICLE POWER TRAIN

Fig 8 shows the components inside Energy Management Subsystem. The first input is the pedal position of the user. The user presses the accelerator and it is received as input to the Power Manager subsystem. Based on the pedal position, the torque is calculated. The position is roughly multiplied by 256 to assume that it is the torque of the motor. Power is calculated based on the motor speed and torque by simply multiplying both. Battery Management System block monitors the battery condition such as State of Charge (SOC). It does not allow deep discharge or over charging current. It sets the battery power and battery limit to the Power Management System. Generator parameters such as current and voltage is monitored and sent to Power Management System.

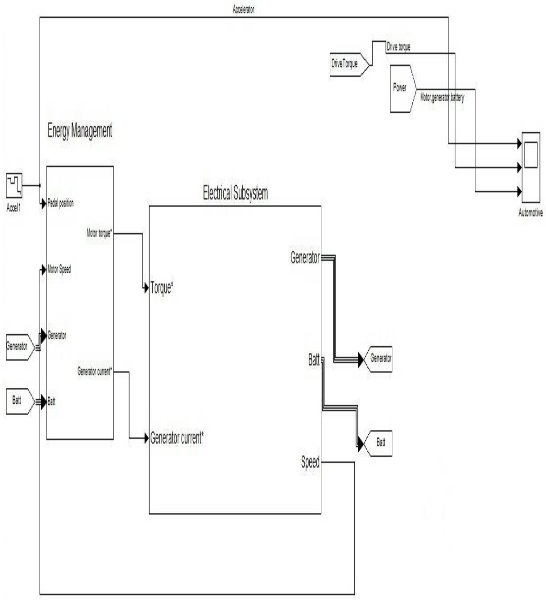

Fig. 7 MATLAB SIMULINK model showing basic blocks such as energy management and electrical subsystem

In Fig. 7, the basic blocks of simulation are shown. Each block is a subsystem. Electrical subsystem consists of the generator, battery and motor. Energy management subsystem consists of the logic for the controller and energy management of battery. Sample acceleration values are provided to the energy management subsystem to test the power splitting between generator and battery.

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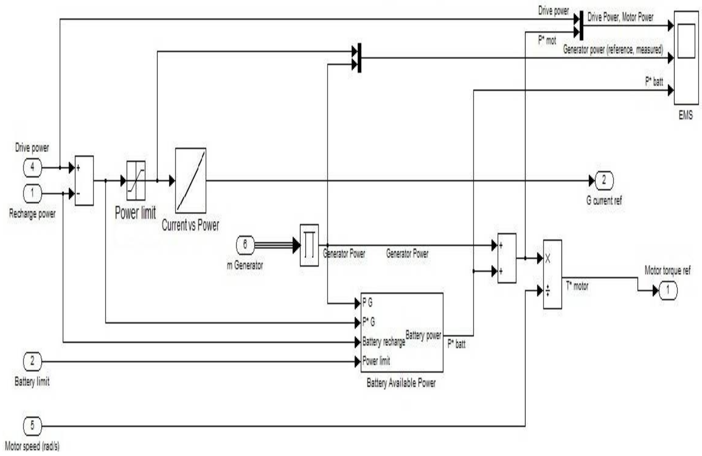

Fig. 8 MATLAB SIMULINK model showing inside blocks of Energy Management subsystem

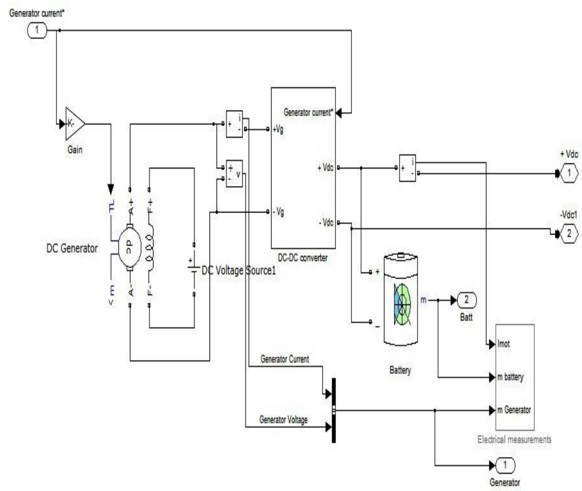

Fig. 9 MATLAB SIMULINK model showing inside blocks of Electrical Subsystem

Fig 8 shows the components inside Energy Management System. When recharge power is subtracted from drive power, it gives the generator power that is required. For various values of power, current that is required from the generator is found. Look up table is formed for this purpose. Based on the current that is required from the generator, mechanical torque has been given as input to the generator. Total power is calculated as addition of generator power and battery power. When total power is divided by the speed of the motor, it gives the torque of the motor. Torque of motor is given as input to the motor and required speed is produced. Battery Available Power block takes care of available SOC of battery.

Fig 9 shows the block inside Electrical Subsystem. This block consists of generator, battery and the converter. DC bus is connected the motor which is placed outside the block. Generator current is received and corresponding mechanical torque is sent as input to the generator. DC-DC converter is placed in series with the generator and battery is connected in parallel with the DC bus. When DC bus voltage is more than battery voltage, battery is charged. When DC bus voltage is less than battery voltage, battery is discharged.

Fig. 10 shows the inner components of DC-DC converter which consists of Bus DC Controller which produces the duty cycle and converter components. Duty cycle is generated based on generator current inputs.

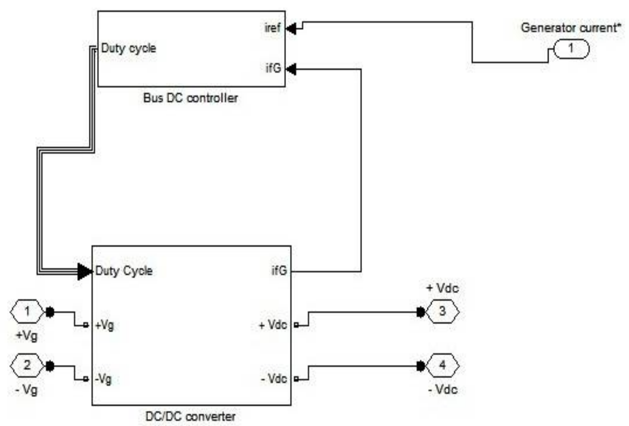

Fig. 10 inside DC-DC Converter Showing Duty Cycle Generator and Converter

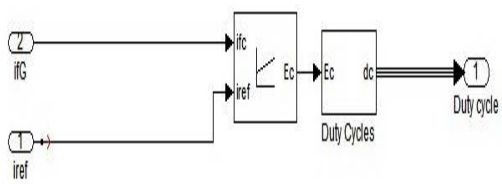

Fig. 11 Inside Bus DC Controller Showing Generation of Duty Cycle

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Fig. 11 shows the inside components of Bus DC Controller. It consists of PI controller and duty cycle generator. PI controller receives generator reference current and actual current as inputs. Fig 12 shows the inner blocks of PI controller. Proportional gain and Integral gain are chosen based on trial and error method. The output of the PI controller is sent to duty cycle generator where duty cycle is determined.

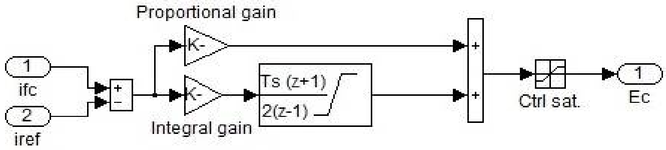

Fig 12 Inside PI Controller

Fig 13 shows the converter components .Where inductor and capacitors are seen that reduce current and voltage ripples. Chopper performs buck converter action.
Fig 14 shows the components inside chopper block. Mathematical modelling of the buck converter is done here. Controlled current and controlled voltage source is used here.

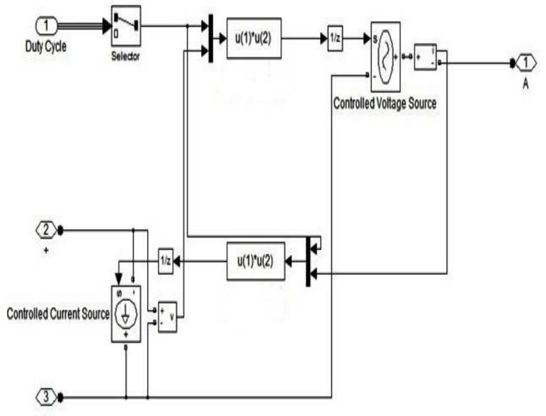

Fig. 14 Inside Chopper Block

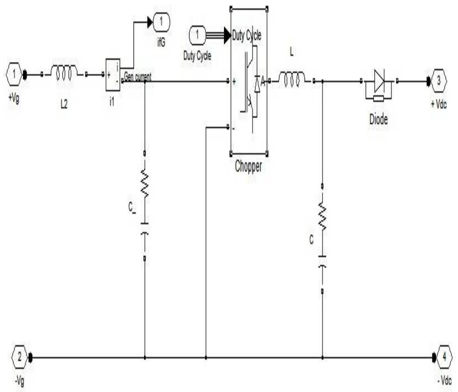

Fig 13 Components inside DC-DC Converter

Thus closed loop system for series hybrid vehicle is designed and simulated. It involved mathematical modelling of the converter and control of DC bus voltage according to loading of the motor. It can be seen that battery supports motor during starting, which means that high current is required. Hence there arises a necessity for another source.
When power of the motor is known, power requirement from the generator and battery can be calculated. The division of power between battery and generator is done based on an algorithm
Generator power is kept constant and based on the power requirement of the motor, power split between battery and motor takes place. This also ensures that number of cycles of charging and discharging of the battery is reduced and hence life of the battery is increased.

IV. HARDWARE DESIGN

Since rating of the converter is above 1000W, it is advisable to go for Full Bridge configuration. It also provides isolation, so that the generator is protected from the fault conditions. This section provides an insight of how to proceed with hardware design of the converter.
There are numerous controllers are available which can be used for this converter. It is always advisable to go for high switching frequency, to reduce the filter requirements. When converter is operated at higher frequency, the PWM and A/D resolution have to be high, so that shoot trough fault does not occur.
TMS and dsPIC can handle high frequency very efficiently. This paper uses dsPIC for its simplicity in programming [8].

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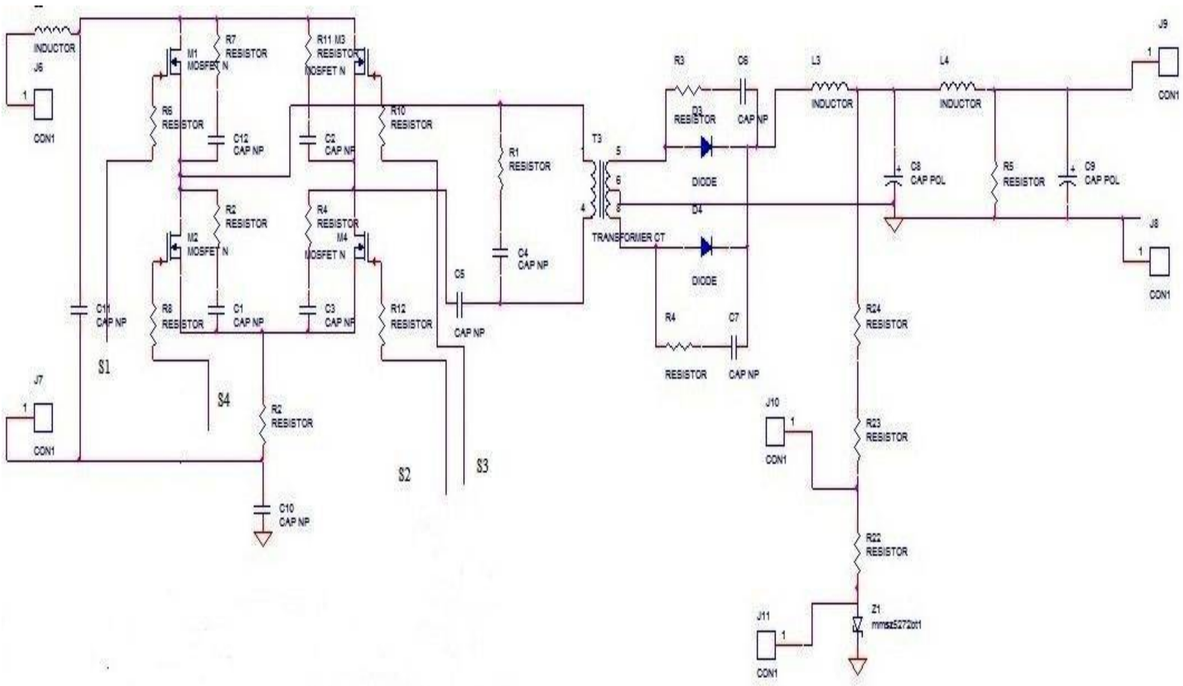

Fig. 16 Full Bridge DC-DC Converter

Fig. 16 shows the complete schematic of Full Bridge DC-DC Converter. It also consists of voltage divider for voltage feedback.

MOSFET is chosen as switch, since it can operate at very high frequency, typically around 100 kHz. MOSFET is selected as per following formulae [9], [10]

$I_{average} = P_{in}/V_{inmin}$ (1) $I_{max} = I_{average}/D_{max}$ (2)

Where D_{max} is maximum duty cycle of the pulse and it may not exceed 50% since it is a full bridge configuration.

MOSFET voltage stress = 2x $(V_o+V_{FET}+V_{DROP})$ (3)

Design of transformer is as follows

$I_{SEC} = I_O \times D$ (4) $I_{PRI} = I_o \times \mathrm{Sqrt}(2D) \times N_s/N_p$ (5)

Various transformer cores are as follows [11]

a) 3C92
b) 3C96
c) 3F35

Power loss density depends on the material that we select. Primary voltage and secondary voltage are specified for number of primary and secondary turns.

Inductor design is as follows

$L_{OMIN} = (V_{PK2} – V_O) \times T_{ONMIN} / I_{MIN}$ (6)

$V_{PK2}= (V_{INMAX} – V_{FETPRI})\ xNs/N_p\text{-}V_{FETSEC}\text{-}V_{DROP}$ (7)

Microchip datasheet is referred for placing components around the microcontroller.

V. RESULTS AND DISCUSSION

Fig. 17 shows the output received after the simulation is performed. The first part of the graph shows the acceleration that is applied to the system. The second graph shows the drive torque and third graph shows the power of generator, motor and battery. Negative power of battery shows charging of the battery and negative power of motor shows

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regenerative braking of it. Green line represents generator power, blue line represents motor power, and pink line represents battery power. It can be seen that, for initial starting of the motor, it receives complete power from the battery. This shows sign of good transient response. Later the generator starts supplying the power and hence charging of the battery takes place whenever motor power is less than generator power. When generator power is less than motor power, battery gets discharged. During regenerative braking, generator is switched off and battery gets charged.

a) From 0 to 4 Seconds:

The accelerator position starts from zero to non- zero value. The Torque of the motor rises, hence the power of the motor also increases. Initially the motor is supplied by the battery and the generator is kept off.

b) From 4 to 8 Seconds:

The torque of the motor reduces, since the accelerator position has come down. The generator has started working. Now the power requirement has come down for the motor and hence the excess power charges the battery that is shown as positive power for battery.

c) From 8 to 12 Seconds:

The accelerator position has risen to the maximum position; hence the power requirement for the motor also increases to maximum. Now the power from generator is not enough, hence both generator and motor supplies the power to motor. Hence the power for battery is shown as positive.

d) From 12 to 16 Seconds:

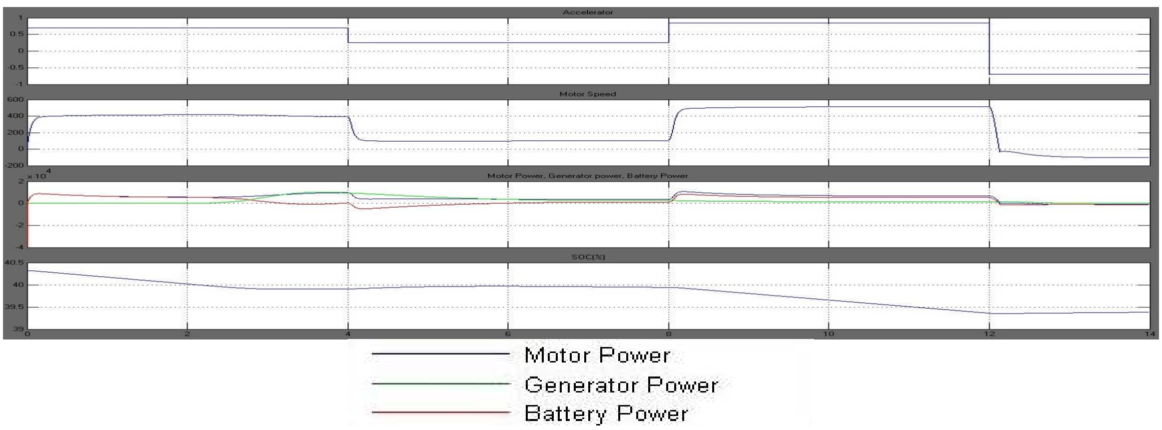
The accelerator is in negative position, i.e. braking action. During braking, the generator is switched off and hence the power is shown is zero. The re-generation produced by the motor gets stored in the battery. Now, both motor and battery power is negative.

From the above result, it is seen that the controller is able to implement the logic that has been formulated to control the hybrid system. It can be noticed that the transient behaviour of the motor is good, since battery is connected directly to the motor side.

As explained in previous chapter using Fig. 5 and Fig. 6, this type of DC-DC converter configuration helps in improving the acceleration of the vehicle and also reduces complexity. This configuration also helps in regenerative braking by saving the energy in the battery.

It can also been seen from the Fig. 5, Fig. 6, Fig. 17 that vehicle is able to achieve maximum speed in short duration. Also complexity of design has been reduced. Rating of DC-DC converter is reduced, as it does not involve battery in its input and hence cost of the product also reduces.

PCB design for the above said converter is done and fabricated as shown in Fig. 18. Controller chosen for this purpose is dsPIC as it can operate at high frequency and complexity of programming is less when compared to other high frequency controller



X-Axis: Time in s
Y-Axis (Motor Speed): Speed in Rad/s
Y-Axis (Power): Power in W
Fig. 17 Waveform showing acceleration, power of motor, battery and generator

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This paper explained about the issues of conventional vehicles and ways to overcome by implementing the hybrid mode of operation. It also showed the advantage of using the series hybrid configuration. This paper also discussed the drawbacks of using other topologies of MIMO converters and explained the advantages of using the proposed MIMO converter. From simulation results, it can also been seen that regenerative power is not wasted, but utilized for charging the battery. Hence maximum efficiency of the system is achieved. Transient response is very good if battery does not contain any control switch between battery and DC bus. This topology can be used in hybrid vehicles for good transient behavior. Mounting the complete components and testing the hardware is future scope of the paper.

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