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A NEW CONTROL STRATEGY FOR HIGH VOLTAGE BI-DIRECTIONAL DC-DC CONVERTER BASED HYBRID ELECTRIC VEHICLE USING STATEFLOW

S.Mamatha, G.Lavanya, G.Divya Mounika

Department of Electrical and Electronics Engineering
St. Johns College of engineering & technology
Yerrakota, Yemmiganur, Kurnool (D), A.P,
Suluvaimamatha4@gmail.com

B.Gururaj, Assistant Professor
Department of Electrical and Electronics Engineering
St.Johns College of engineering & technology
Yerrakota, Yemmiganur, Kurnool (D), A.P,
Anilgururaj009@gmail.com

Abstract

A couple of decade ago when auto engineers decided to increase the voltage level of electrical power system drive, it was the advancement of silicon technology supporting their dream. Today the power electronics circuits play an important role in the success of electric, hybrid and fuel cell vehicles. Typical power electronics circuits in hybrid vehicles include electric motor drive circuits and DC/DC converter circuits.This paper aims at reviewing the use of different power electronics devices in hybrid electric vehicles.Unlike conventional software development methods,the bottom layer software and the application layer software are developed separately based on the research background of battery management system(BMS) of hybrid car with integrated starter generator (ISG).The bottom layer software is made by Handwork,While the application layer software is developed by simulink Stateflow and Targetlink.The simulation results show that the code generated automatically can meet the requirement of the system function and converge seamlessly with the bottom layer code.This method can greatly shorten the software development cycle,reduce the development cost and improve the efficiency of the software update .

KEYWORDS: Buck converter, Boost Converter, Galvanic isolation, Hybrid Electric Vehicles (HEVs), Multilevel Converter, Planetary Gear, Power Split HEV, PWM Rectifier.

I. INTRODUCTION

The near-future technologies related to hybrid electric vehicles (HEV) are the most promising alternatives to cope with the reduction of greenhouse gases in the car industry. In particular, plug-in HEV and vehicle-to-grid (V2G) concepts will have a tremendous impact not only on the reduction of greenhouse gases but also on electricity distribution systems.

In this paper, the key design aspects of hybrid electric vehicle are discussed and how it can offer an efficient solution to some of the key issues, the potential benefits of using Model-Based Design in the engineering workflow. Traditionally, this method has been used primarily for controller development. One of the goals of this paper is to show how Model-Based Design can be used throughout the entire system design process.

In recent years, research in hybrid electric vehicle (HEV) development has focused on various aspects of design, such as component architecture, engine efficiency, reduced fuel emissions, materials for lighter components, power electronics, efficient motors, and high-power density batteries. Increasing fuel economy and minimizing the harmful effects of the automobile on the environment have been the primary motivations driving innovation in these areas.

In section 2, we offer a short primer on HEVs and the various aspects of the design. Section 3 is devoted to Model-Based Design and the applicability of the approach to HEV development.

II. BASIC DESIGN OF HYBRID ELECTRIC VEHICLE

A block diagram of one possible hybrid electric vehicle architecture is shown in Figure 1. The arrows represent possible power flows. Designs can also include a generator that is placed between the power splitter and the battery allowing excess energy to flow back into the battery.

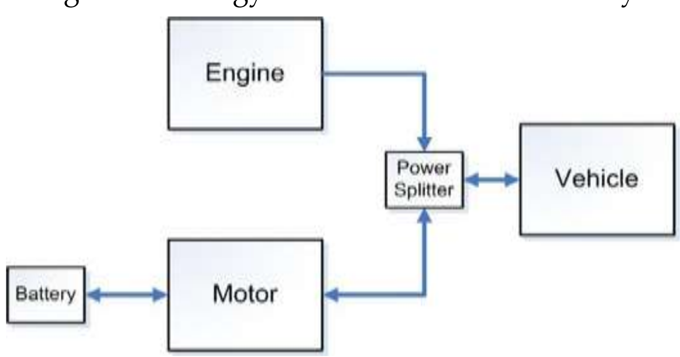

Figure 1: The main components of a hybrid electric vehicle.

Conceptually, the hybrid electric vehicle has characteristics of both the electric vehicle and the ICE (Internal Combustion Engine) vehicle. At low speeds, it operates as an electric vehicle with the battery supplying the drive power. At higher speeds, the engine and the battery work together to meet the drive power demand. The sharing and the distribution of power between these two sources are key determinants of fuel efficiency. Note that there are many other possible designs given the many ways that power sources can work together to meet total demand.

Engine design - The key elements of engine design are very similar to those of a traditional ICE. Engines used in an HEV are typically smaller than that of a conventional vehicle of the same size and the size selected will depend on the total power needs of the vehicle.

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Battery design - The main considerations in battery design are capacity, discharge characteristics and safety. Traditionally, a higher capacity is associated with increase in size and weight. Discharge characteristics determine the dynamic response of electrical components to extract or supply energy to the battery.

Motor - Motors generally used in HEV systems are DC motors, AC induction motors, or Permanent Magnet Synchronous Motors (PMSM). Each motor has advantages and disadvantages that determine its suitability for a particular application. In this list, the PMSM has the highest power density and the DC motor has the lowest. [3].

Power Splitter - A planetary gear is an effective power- splitter that allows power flows from the two power sources to the driveshaft. The engine is typically connected to the sun gear while the motor is connected to the ring gear.

Vehicle dynamics - The focus is on friction and aerodynamic drag interactions with weight and gradability factors accounted for in the equations.

Overall System Design - The first step in the design process of the hybrid power train is to study the maximum torque demand of the vehicle as a function of the vehicle speed. Ratings of the motor and the engine are determined iteratively to satisfy performance criteria and constraints. The acceleration capabilities are determined by the peak power output of the motor while the engine delivers the power for cruising at rated velocity, assuming that the battery energy is limited. Power sources are coupled to supply power by the power-splitter, and the gear ratio of the power-splitter is determined in tandem. The next steps include developing efficient management strategies for these power sources to optimize fuel economy and designing the controllers. The final steps focus on optimizing the performance of this system under a variety of operating conditions.

III. CIRCUIT TOPOLOGIES

Fig. 2 shows the general powertrain lay out of hybrid electric vehicle [1], [5]. The power electronics unit consists of a bidirectional DC/DC converter that links the lower voltage hybrid battery and the higher voltage DC bus, and three motor drive circuits that control the front and rear motor/generators.

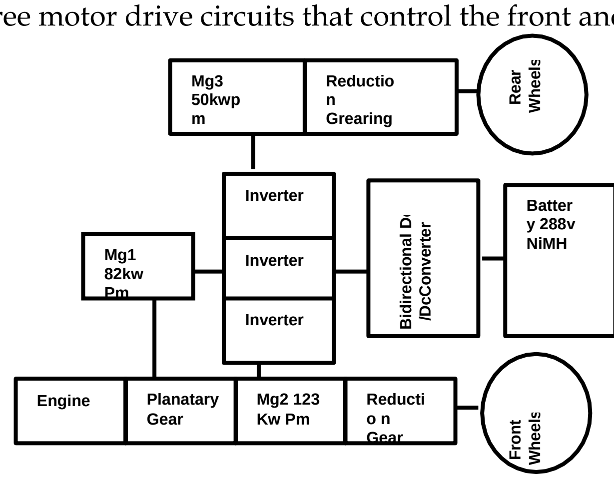

Figure 2:Typical layout of HEV .

Fig. 2 shows that other than propelling the vehicle, power electronics converters are used for activation and control of all other loads such as air conditioning, power steering, fans, pumps, video, and many other hotel and ancillary loads in sports utility vehicles.

IV. ADVANCED DRIVE TRAIN ARRANGEMENT FOR HYBRID ELECTRIC VEHICLE

An Internal Combustion Engine (ICE) and an electric motor (EM) in series or parallel configurations propel HEVs. The ICE helps to increase the drive range and electric motor enhances the fuel economy and efficiency.

HEVs are generally categorised as series or parallel hybrid. In series hybrid, EM propels the vehicle completely and in parallel hybrid, both EM and ICE is responsible to propel the vehicle in most optimised way in fuel efficiency and drive range. Now, series– parallel and complex HEVs have also been developed to improve the power performance and fuel economy [1], [2], [3].

A. *Series HEV*

A series hybrid vehicle, an ICE is generally run at an optimal efficiency point to drive a generator and charge the propulsion batteries on-board the vehicle, as shown in Fig.3 Whenever the battery is at its predetermined minimum, the ICE is turned on and charges the battery. The ICE turns off again when the battery has reached a desirable maximum value. The battery charge must be maintained to 65-75%. There is no mechanical connection between ICE and wheels in this topology.

As the ICE is running at its optimal speed and torque combination, the fuel consumption is low and efficiency is high. But due to two stages of energy conversion, the energy loss is high during conversion. A series hybrid vehicle is more applicable in city driving.

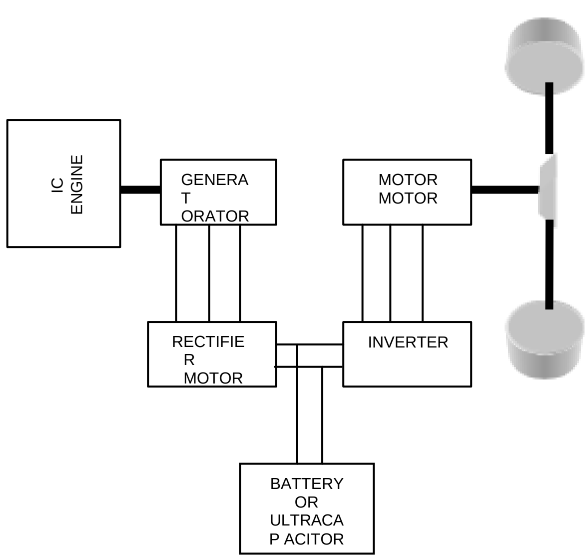

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Figure 3:Typical layouts of a series HEV drive train.

B.*Parallel HEV*

A hybrid vehicle with the parallel configuration has both the ICE and the traction motor mechanically connected to the transmission as shown in fig. 3. The ICE and EM both are capable to propel the vehicle alone as well as in combination depending on the required torque. But, generally EM is used to propel the vehicle at low speed and ICE is used to drive the vehicle at higher speeds. So at

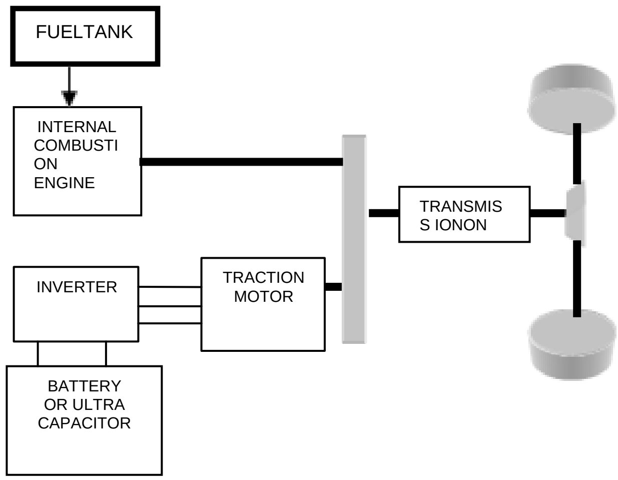

Figure 4 : Typical layout of parallel HEV drive

higher speeds EM works as a generator and charges the battery. In this topology of HEV, it is possible to utilize the maximum efficiencies of both the EM and ICE. This results in low fuel consumption and less energy loss because of lesser energy conversion stages as compared to the series HEV drive train.

C.Series-Parallel HEV

The series-parallel HEV is a combination of the series and parallel hybrids. There is an additional mechanical link between the generator and the electric motor and generator, as shown in Fig. 5. So the cost and complexity of this configuration is more than that of simple parallel or series configuration.

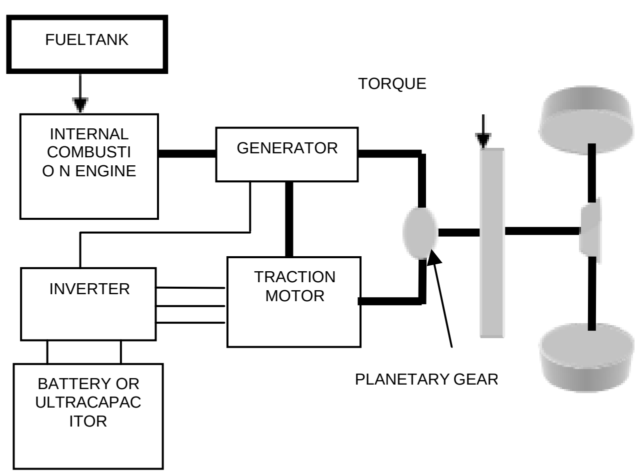

Figure 5:. Typical drive train configuration of a series-parallel HEV

The series parallel HEV can be engine intensive where ICE is more active, and electric intensive in which EM is more active. Commonly, EM is used to start the vehicle and ICE alone propels the vehicle in normal drive in engine intensive whereas both EM and ICE drive the vehicle in electric intensive. When acceleration is needed, the electric traction motor is used in combination with the ICE to give extra power in both of the configurations. During braking or deceleration, the motor acts as a generator to charge the battery and, in stand still, the ICE can continue to run and drive the generator to charge the battery, if needed.

D.Complex HEV

Another form of series-parallel hybrid configuration is also known as power split hybrid shown in Fig. 6. A power split device such as planetary gear allows the power path from engine to the wheel that can be either mechanical or electrical. The main principle behind this system is decoupling of the power supplied by the source from the power demanded by the driver. A combustion engine has lower torque at less RPM and larger engine is required to accelerate the vehicle from stand still. An Electric motor has maximum torque at standstill. In power split hybrid mode, a smaller less flexible and highly efficient engine can be used [9], [12].

General Motor's Two Mode Hybrid Full size trucks and SUVs, the BMW X6 active Hybrid and Mercedes ML450 Hybrid are few examples of Power split complex hybrid vehicles

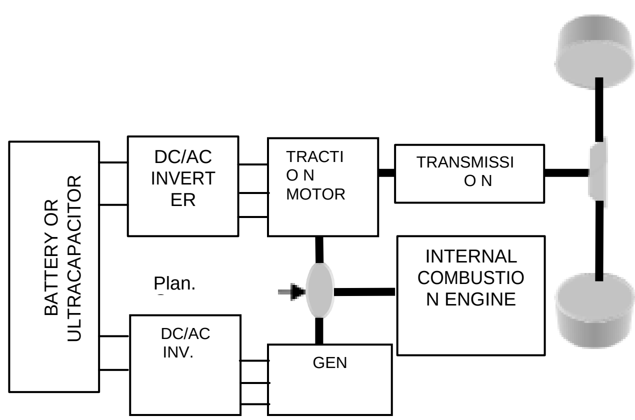

Figure 6:schematic of a complex HEV drive train

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V. HIGH POWER DEVICES IN HEV

Commonly used power electronic circuits in HEVs include rectifiers, inverters, and DC/DC converters and Dc/Ac inverters. Fig. 7 shows multiple voltages more hybrid electric vehicles (MHEV) electrical power distribution system. Most of the loads shown in the figure require power electronic controls. The power electronics converters are used to change the voltage levels and also convert the form of electrical power.

Power electronic control provides the auto designer to implement various ideas to increase the comfort and lavishness in the vehicle either during on drive or at standstill. This section discusses the basic power electronic circuits used in hybrid vehicles in general.

A.Bi-directional DC/DC Converter

A bi-directional DC/DC converter is required to boost the 42-volt (low voltage) DC power level from the HEV battery to300 volt (high voltage) i.e. a power level required for propulsion. Another low power DC/DC converter connects the Hybrid battery to the low voltage auxiliary battery for other control action.

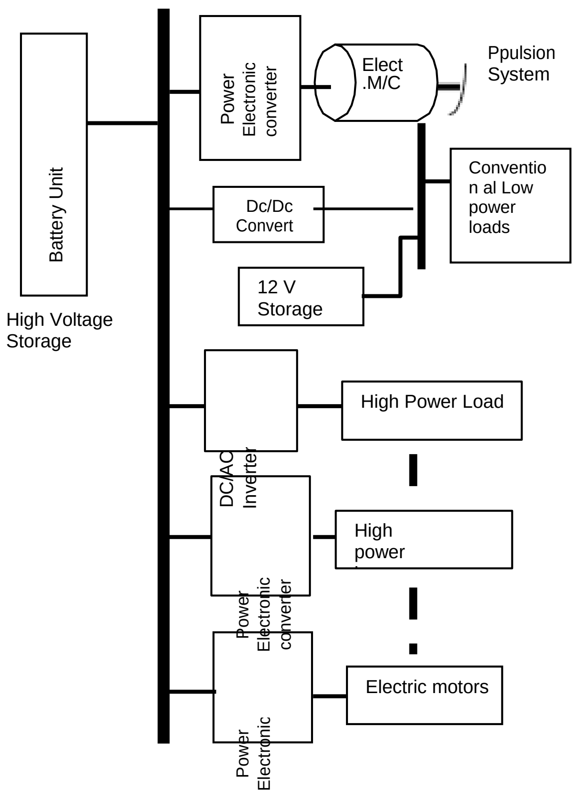

Figure 7:Typical electrical power distribution system of MHEV

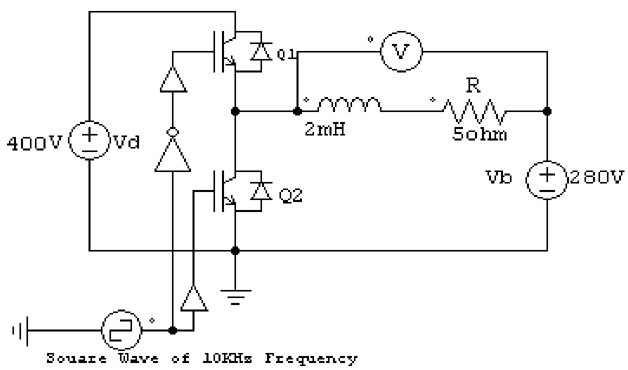

Figure 8(a): Bi-directional DC/DC converter

A typical bi-directional DC/DC Buck Boost converter is shown in fig.8 (a)[1] [7], [16]. During buck operation Q1 is closed and Q2 is open. The power flows from higher side V_d to lower side V_b. The voltage across the R-L load

given by equation-

$$V_L \square V_D \square V_B$$

and the current through the inductor increases to I_{max} depending on the values of R and L and during T_{off} current flows through the FWD of Q2; the load current decreases to the final value. The average value of the load current is given as

$$I_L \square \frac{I_{max} \square I_{min}}{2}$$

In boost operation, power flows from V_b to V_d. When Q2 ison, current flows through R-L and Q2 building inductor current and

$$V_L \square \square V_B$$

When Q2 switches off, the inductor current flows through the FWD of Q1 and charges the battery voltage

$$V_D \square V_B \square V_L$$

Fig.8 (b) and (c) shows the output waveforms of DC-DC converter shown in Fig. 8(a) with 50% duty cycle. The high bus voltage has been assumed as 400 v and lower bus voltage as 280V, which are the typical values for more HEV.

Amp)

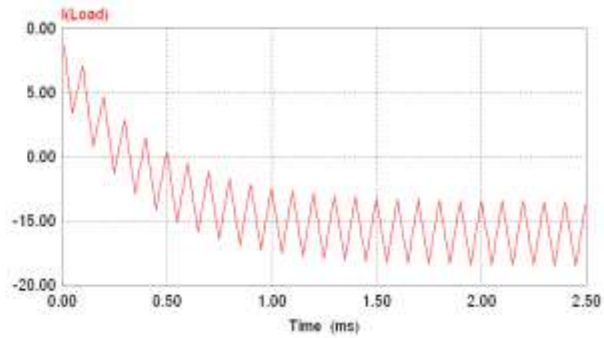

Figure 8(b):load current of bi-directional DC-DC

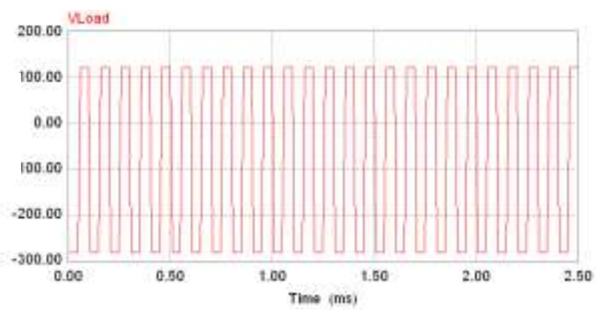

Figure8(c):load voltage of bi-directional DC-DC

B. ***Voltage Source Inverter***

Voltage source inverters (VSI) are a three-phase inverter, which links DC/DC converter and the propulsion motor [29]. In a HEV, inverters are also used to control the generator and other auxiliary loads. Fig. 9(a) shows the power electronic circuit of a VSI, connected to the electric motor [4].
The switching frequencies of the controlled switches are controlled by pulse width modulated signal to obtain the
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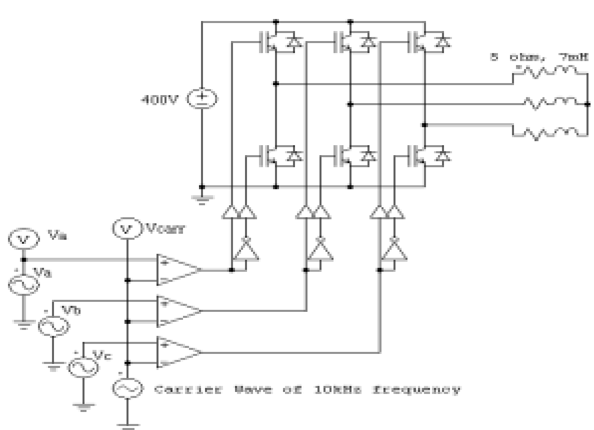

Figure 9 (a):VSI simulated on PSIM.

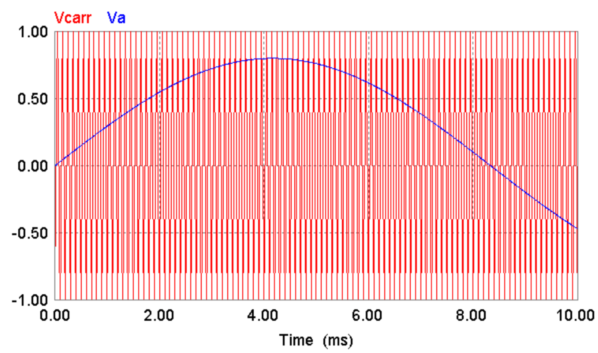

Figure. 9(b): PWM Signal for VSI

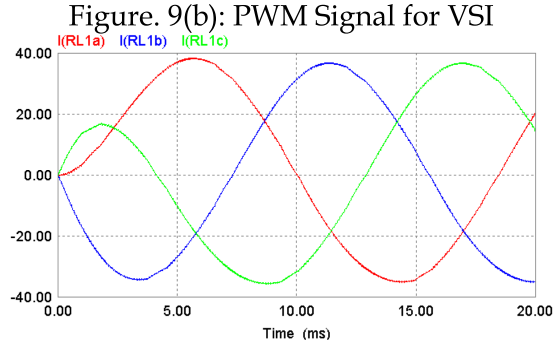

Figure. 9(c): AC Output current of VSI

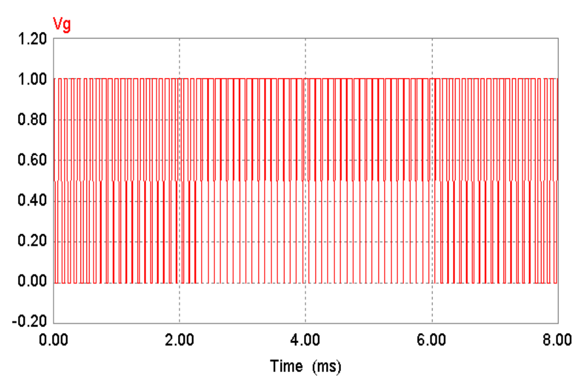

Figure 9(d): Typical gating signal for VSI

Sinusoidal waveform of required frequency at the output. High switching frequency keeps the harmonics away from the output waveform. Use of IGBT also reduces the harmonics in the output. With 10KHz frequency of carrier waveform and 50% duty cycle we obtain the three-phase current s shown in fig. 9(c). The gating signal is shown in fig 9(d).

C.Isolated Bi-directional DC/DC Converter

Fig. 10 shows schematic diagram of isolated bi- directional DC/Dc converter used in HEVs. DC/Dc converters in HEV transfer the power from low voltage battery to high voltage transmission bus. Many other power electronic devices are terminating on this bus. Galvanic isolated DC/DC converter will protect the high voltage circuits from any undesirable harmonics, noise etc [2], [7], [8].

The primary bridge inverter switches at 20 to 50 kHz, with a 50% duty ratio. The output of the primary is a square wave voltage, which is applied to the primary winding of the isolation transformer. The secondary winding of the transformer will therefore have a square wave voltage,which is applied to the primary winding of the isolation transformer.The secondary winding of the transformer will therefore have a square wave voltage.

Without any control at the gating of the secondary bridge converter, the voltage of the secondary of the transformer is rectified through the four freewheeling diodes. The output voltage will fluctuate with load conditions and change the primary voltage.

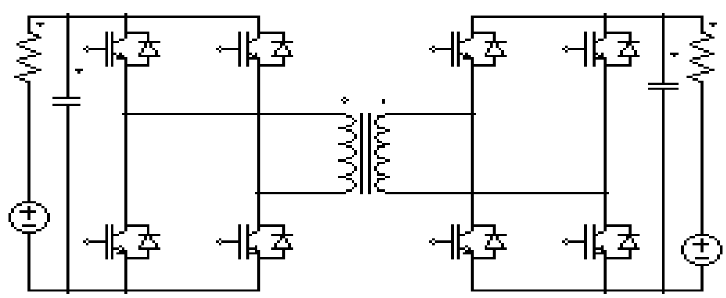

Figure 10 : Power circuit isolated bi-directional converter

D.PWM Rectifier

During regenerative breaking, the VSI is operated as a PWM rectifier as shown in fig. 11 (a). When the motor speed is below the base speed of the constant power region, the operation is same as an isolated boost. When the motor speed is above the base speed of the constant power region, the generator develops a back emf much larger than the DC link voltage, especially when a large constant power speed rang is designed.

The PWM rectifier circuit is simulated using 10k Hz carrier frequency for IGBTs. As shown in fig.11 (b)

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and 11 (c) the harmonic level has less value in PWM technique. Using IGBT has the added advantage of high frequency carrier signal. The current through the filter capacitor contains some level of harmonic, which is not dominating in DC output current or voltage. The IGBT are fired at 50% baud rate.

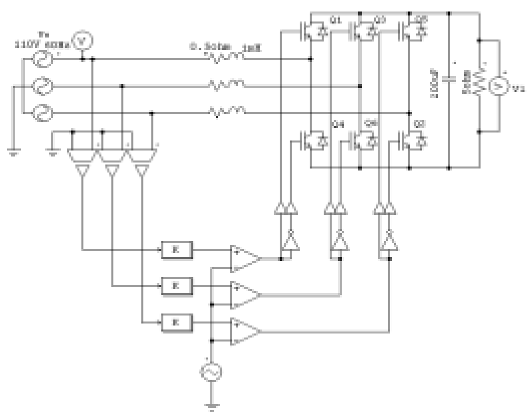

Figure 11(a) : PWM rectifier simulated on PSIM

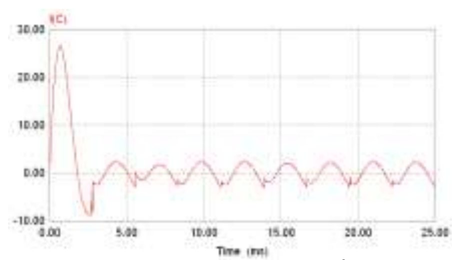

Figure 11(b) :Output capacitor current of PWM rectifier

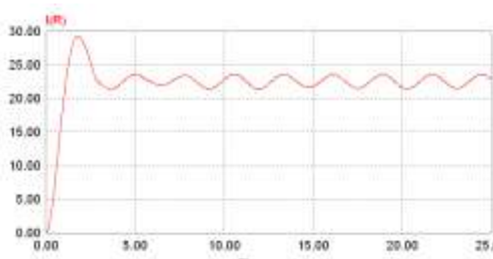

Figure 11 (c): DC output current of PWM rectifier

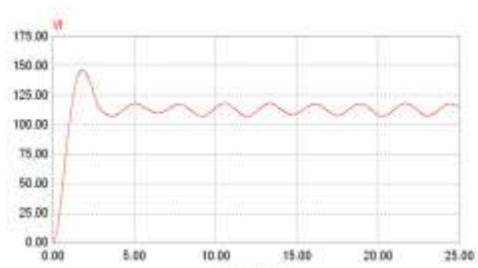

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Figure .11 (d): DC output voltage of PWM rectifier

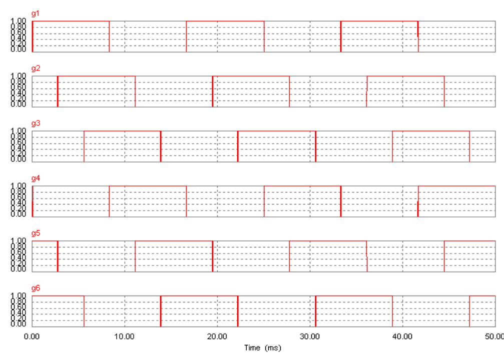

Figure 11 (e):Gating signal for PWM rectifier

VI. VEHICLE DYNAMICS

Modeling the vehicle dynamics can be a challenging task. When creating any simulation model it is important to consider only the effects that are needed to solve the problem at hand. Superfluous details in a model will only slow down the simulation while providing little or no additional benefit. Because we are primarily interested in the drive cycle performance, we will limit our vehicle model to longitudinal dynamics only. For example, the vehicle was initially modeled as a simple inertial load on a rotating shaft connected to the drive train.

ENGINE

A complete engine model with a full combustion cycle is also too detailed for this application. Instead, we need a simpler model that provides the torque output for a given throttle command. Using Simulink® and SimDriveLine™, we modeled a 57kW engine with maximum power delivery at 523 radians per second, as shown in Figure 12.

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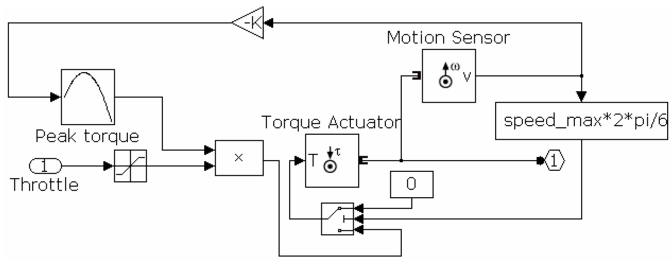

Figure 12: Engine modeled using blocks from the SimDriveline™ library.

SYNCHRONOUS MOTOR/GENERATOR

The synchronous motor and generator present an interesting example of electromechanical system modeling. Standard techniques for modeling synchronous machines typically require complex analysis of equations involving electrical and mechanical domains. Because the input source to this machine drive is a DC battery and the output is AC, this would require the creation of complex machine drive and controller designs – often a significant challenge at this stage.

An averaged model that mathematically relates the control voltage input with the output torque and resulting speed is a useful alternative. This simplification allows us to focus on the overall behavior of this subsystem without having to worry about the inner workings. Furthermore, we can eliminate the machine drive by simply feeding the DC voltage directly to this subsystem.

With this averaged model, we only need a simple Proportional-Integral (PI) controller to ensure effective torque control. The Motor/Generator subsystem design will be explored in more detail in the next section.

POWER-SPLITTER

The power-splitter component is modeled as a simple planetary gear, as shown in Figure 6. With these building blocks, more complex gear topologies can easily be constructed and tested within the overall system model.

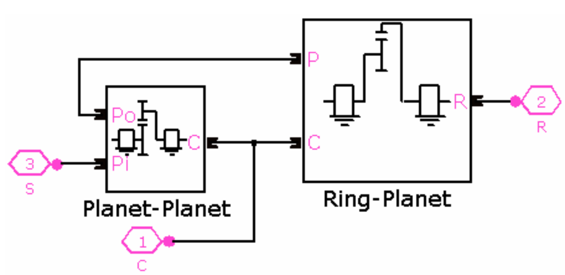

Figure 13: Power-splitter modeled as a planetary gear with connections.

POWER MANAGEMENT

The power management subsystem plays a critical role in fuel efficiency.

The subsystem has three main components:

- Mode logic that manages the various operating modes of the vehicle.
- An energy computation block that computes the energy required to be delivered by the engine, the motor, or both in response to gas pedal input at any given speed.
- An engine controller that ensures the engine is the primary source of power and provides most of the torque. The motor and generator controllers provide torque and speed control.

MODE LOGIC

For efficient power management, an understanding of the economics of managing the power flow in the system is required. For example, during deceleration, the kinetic energy of the wheels can be partially converted to electrical energy and stored in the batteries. This implies that the system must be able to operate in different modes to allow the most efficient use of the power sources.

We used the conceptual framework shown in Figure 14 to visualize the various power management modes.

Algorithm design starts with a broad understanding of the various possible operating modes of the system. In our example, we identified four modes—low speed/start, acceleration, cruising, and braking modes. For each of these modes, we determined which of the power sources should be on and which should be off. The conceptual framework of the mode logic is easily implemented as statechart. Statecharts enable the algorithm designer to communicate the logic in an intuitive, readable form.

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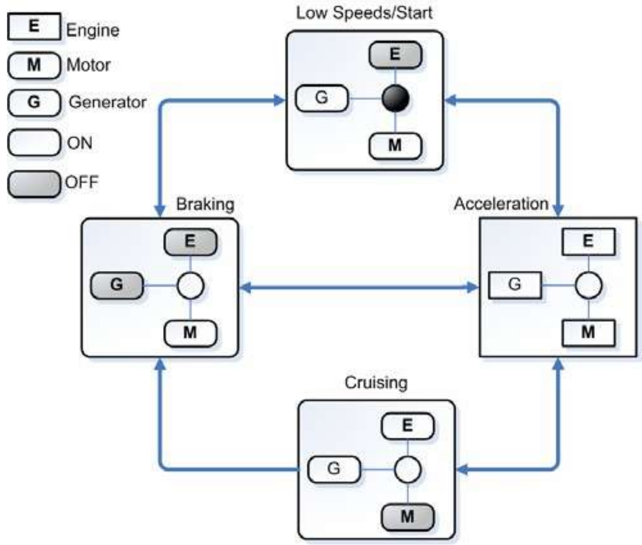

Figure 14: Mode logic conceptualized for the hybrid vehicle.

The Stateflow® chart shown in Figure 8 is a realization of the conceptual framework shown in Figure 14 While very similar to the conceptual framework, the Stateflow chart has two notable differences. The "acceleration" and "cruise" states have been grouped to form the "normal" superstate, and the "low speed/start" and "normal" states have been grouped together to form the "motion" superstate. This grouping helps organize the mode logic into a hierarchical structure that is simpler to visualize and debug.

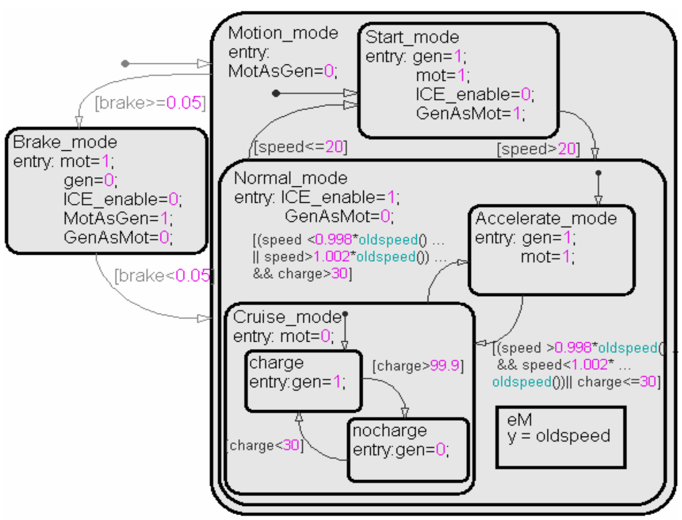

Figure 15: Mode logic modeled with Stateflow®.

VII. CONCLUSION

In this paper, we first described a typical HEV design and gave an overview of the key challenges. We discussed how the multidomain complications arise from the complex interaction between various mechanical and electrical components—engine, battery, electric machines, controllers, and vehicle mechanics. This complexity, combined with the large number of subsystem parameters, makes HEV design a formidable engineering problem.

We chose Model-Based Design as a viable approach for solving the problem because of its numerous advantages, including the use of a single environment for managing multidomain complexity, the facilitation of iterative modeling, and design elaboration. Continuous validation and verification of requirements throughout the design process reduced errors and development time.

Our first step in the development process was the realization of a system-level model of the entire HEV. The subsystem components were averaged models, which underwent model elaboration with requirements refinement and modifications in parallel. We showed how statecharts can be used to visualize the operating modes of the vehicle. After each component model was elaborated, we integrated it into the system-level model, compared simulation results of the averaged and detailed models, and noted the effect of model elaboration on the outputs. When simulation times grew long as we moved towards a fully detailed model, we introduced techniques to alleviate this issue.

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