Power Conversion in Mild Hybrid Electric Vehicles

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ABSTRACT

Modern Mild Hybrid Electric Vehicles (MHEV) are designed to provide many of the fuel economy benefits of full hybrid electric vehicles with only modest increments in cost and complexity. The addition of a 48 V battery means a MHEV is a dual−voltage vehicle, which presents its own unique design challenges. These design challenges are centered on managing the charge and discharge cycles of the dual battery system while attempting to maintain the highest overall system efficiency.

The methods for overcoming these design challenges are highlighted in this paper, including sub−system design details for maximizing cost and efficiency. The realization of power converters using Automotive Power Modules and GaN devices are also explored.

This topic is of interest to engineers wishing to understand the complexities of incorporating a superior converter design into a MHEV.

INTRODUCTION

With environmental conditions, and in particular air quality, becoming a growing concern in many parts of the world, vehicle emissions of CO_2 need to be cut by reducing the average vehicle fuel consumption. One method of achieving this is to add hybridization to vehicles powered by conventional Internal Combustion Engines (ICE).

In a typical vehicle, the traction power systems must be able to operate over a very wide range of vehicle power and speed conditions, this can be described as the vehicle's torque−speed range. The hybridization of a vehicle is the process of adding a second power source, most likely an electric motor that is driven by a second battery.

The use of a hybridized powertrain allows the system designer the freedom to arrange the two power sources in ways that optimize each of them during different parts of the torque−speed range. The electric machine is able to provide a very large amount of torque, and is useful when accelerating the vehicle, but this torque is only available for limited amounts of time. The specific time available is dependent on both the size of the battery and the torque output of the electric machine. The addition of a source of high torque power means the ICE can be significantly downsized, allowing the vehicle to be considerably more fuel efficient overall. However, the addition of the electric power source is no trivial engineering matter and requires a design approach that considers the impact on many of the vehicle's systems.

Traditional electrification has been achieved by adding a high−voltage battery, typically in the 300 V to 400 V range, and a high performance electric machine directly coupled to the ICE powertrain. These ‘Full’ Hybrid vehicles have been the defining class of fuel efficient vehicles and are very attractive from an increased efficiency standpoint. However, they add a considerable amount of cost and weight to the vehicle.

The 48 V vehicle system architectures have received a considerable amount of attention in recent days. These systems can be thought of as a partial step towards a Full Hybrid vehicle. They are referred to as ‘Mild Hybrids’ and are constructed using a relatively compact 48 V battery system, a high performance electric machine and one, or multiple, additional 48 V electrified sub−systems. The lower cost of 48 V systems has attracted the attention of many automotive OEMs and they may soon be a part of all vehicle manufacturers’ portfolios.

THE 48 V ARCHITECTURE

The choices in 48 V architectures are quite large and constantly increasing. The most basic system includes a battery, an integrated starter−generator (ISG), a 48 V to 12 V converter, and one or more 48 V loads. Since 48 V vehicles still retain the 12 V battery and multiple 12 V loads, it is likely that these systems will exist as dual voltage architectures for the foreseeable future.

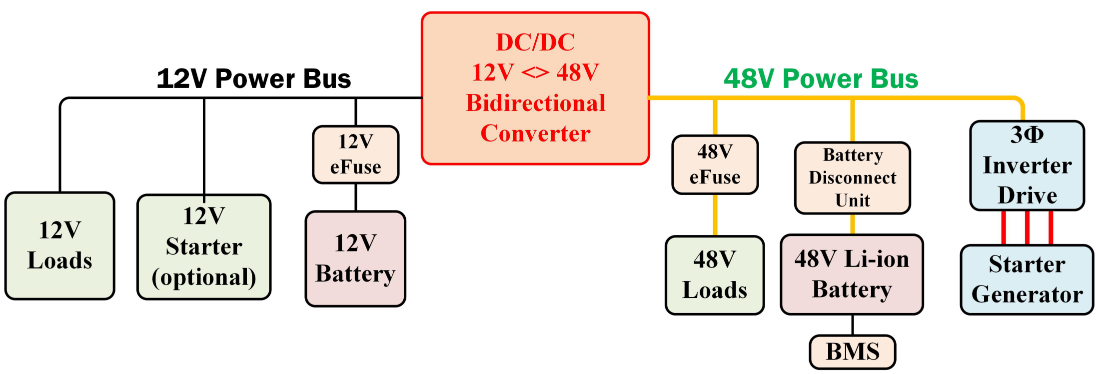

Figure 1. A 48 V Mild Hybrid Electrical System

Within these dual−voltage systems a plethora of new configurations are possible. Since the 48 V system is fundamentally capable of sourcing higher power levels, it is capable of powering peripherals, like the 48 V E−Turbo and 48 V E−Roll stabilization systems.

On the 48 V system side, the ISG is the primary component and is responsible for generating all of the vehicle’s electrical power as well as being used for vehicle starting. It also performs regenerative energy recovery during vehicle braking. ISG’s come in many configurations and power levels, each with their own specific implementation goals.

Presently, the 12 V battery side of the dual voltage system remains as is, minus the 12 V alternator. Since there is no generating source of 12 V power, there is a need for a converter to transfer the 48 V generated power to the 12 V system. Even though the converter will be designed with high efficiency, it will still impose a loss penalty on all 12 V loads, since their power will be delivered through the converter.

The 48 V to 12 V power converter is a necessary addition to the MHEV dual−voltage system. The requirement to provide power flow in both directions dictates that it be designed to function bidirectionally. The typical power range for these converters is in the 1 kW to 3 kW range, and to maintain high efficiency over this large power range a multi−stage interleaved buck−boost converter is currently the most popular topology choice. The buck topology permits power to flow from the higher voltage side to the lower voltage side. Similarly, the boost topology permits power flow in the opposite direction. The multi−phase interleaved design supports the ability to combine many individual converter phases into a single high−power converter.

When the converter is under heavy load, all of the phases will be operational, but during periods of lighter load some of the phases can be switched off, resulting in lower losses and better efficiency.

CONVERTER TOPOLOGIES

The bidirectional converter required for the MHEV application can be configured using several different topologies. The most common is the interleaved, synchronous buck−boost, bidirectional voltage converter. This converter type is designed to have several identical phases, each of them connected in parallel, functioning as a much larger converter. These “interleaved” phases work together and can be disabled when required. The diagram of a single phase of this converter is shown in Figure 2.

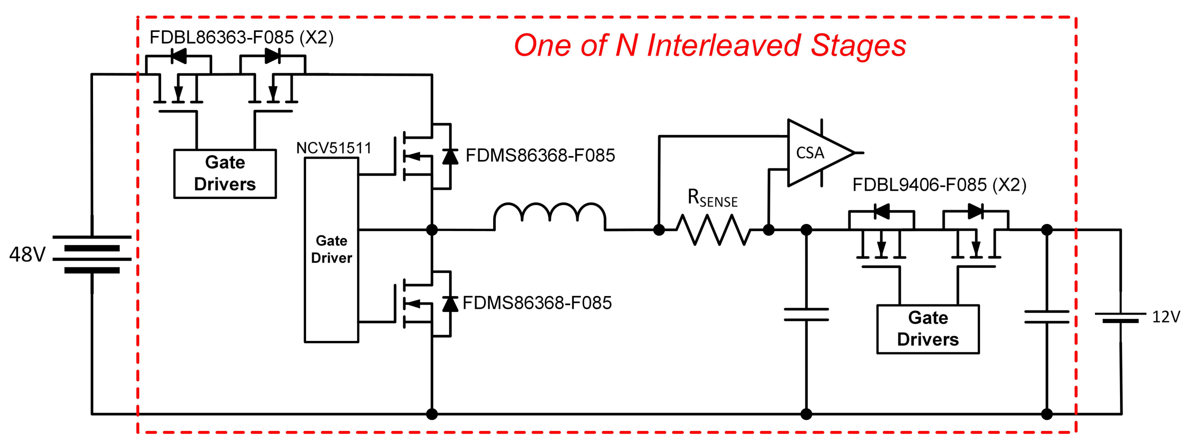

Figure 2. Bidirectional Converter – Single Phase

The main blocks that constitute this converter are the source−disconnect switch, buck−boost half−bridge, the current sensing stage, main inductor and the load−disconnect switch.

The source−disconnect switch is used to disconnect each converter phase from the 48 V battery.

The main circuit is a buck−boost converter configured in a synchronous topology, which is used when higher efficiency and bidirectional operation are required. The synchronous topology improves circuit efficiency by controlling the power switches in a way where they are full−on during the majority of both conduction and recirculation periods.

The synchronous buck−boost converter is actually two switching circuits combined into a single stage. The power switches control the current flow in the main energy−converting component; the inductor. The inductor current is the primary variable that needs to be controlled in the entire converter, as it is of paramount importance for maintaining good system accuracy.

The direction of the inductor current determines the direction of the power flow, and thus determines which battery receives current from the other. The system controller determines the direction of current, by generating the proper switch pattern to provide the desired current direction. For instance, if the 12 V battery requires charge, then the switch patterns will be controlled to produce current flow as shown in the buck example of Figure 3. If the 48 V battery requires charge, then the switch patterns will be generated to produce current flow as shown in the boost portion of Figure 3.

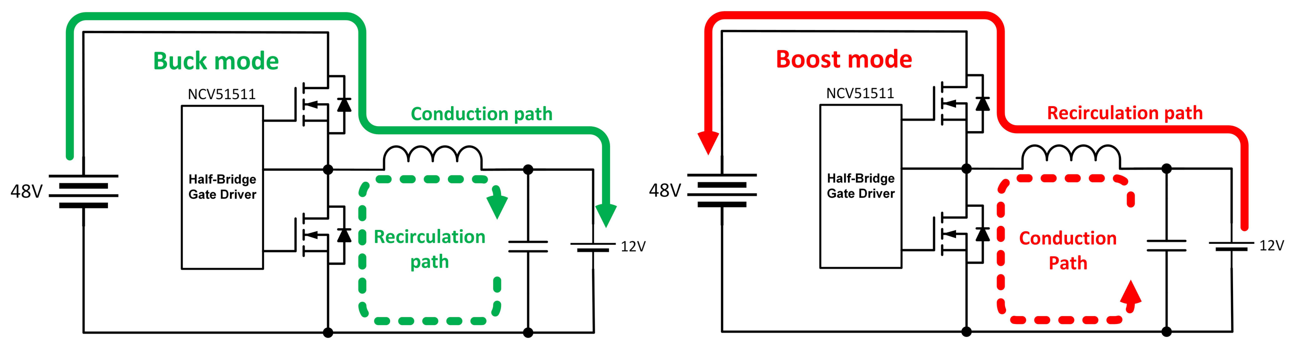

Figure 3. Buck−Boost Conversion

The current sensing stage is responsible for monitoring the inductor current and transferring its value to the system controller. The use of a precision shunt resistor is a popular current sensing method. The shunt resistor is placed in the path of the inductor current and based on the principles of Ohm's law, the changes in the current flow results in a change in the voltage across the shunt. A Current Sense Amplifier (CSA) is used to monitor the voltage across the two terminals of the shunt. The CSA amplifies the shunt voltage to a signal level appropriate for the input to the system controllers' analog to digital converters (ADC).

During normal operation the shunt voltage can vary from zero to 48 V with respect to ground. At the same time, the shunt's differential voltage can be very small, in the order of tens or hundreds of millivolts. This large difference in the desired versus the undesired voltage signal level present a formidable problem for most amplifiers. The amplifier is required to amplify small differential signals and provide high common mode voltage rejection, while withstanding transient voltages up to 80 V. In order to address the problem, three amplifier specifications need to be carefully selected:

- Common Mode Voltage Range (the wider the better)
- Input Offset Voltage (the smaller the better)
- Common Mode Rejection Ratio (the higher the better)

In conventional Operational Amplifiers the input terminal voltages are limited to the supply rails ±0.6 volts, thus dramatically limiting the common mode voltage range. In recent years dedicated current sense amplifiers provide a much larger common mode voltage range of up to 80 V. They also provide high precision, as low as 10 μV offset. This enables system designers to achieve highly accurate and fast current monitoring systems.

A single phase representation of the converter is shown in Figure 2, this is one of many phases required to create the full power 48 V to 12 V converter. The paralleling of several identical phases creates a converter capable of high levels of power. A configuration known as interleaving allows each phase to operate independently but their outputs to be combined, resulting in a product that would normally require a much larger converter. Each of the individual phases is configured to produce its output current with a slightly different phase angle with respect to each of the other phases. These phase angle offsets also reduce the ripple at the output capacitors.

There are several reasons for using interleaving rather than designing a single larger converter. First, the current levels in each phase are reduced to alleviate the stress on the power switches, conductors, and inductor. Each phase can be disconnected independently as necessary and the converter power level design can be made modular.

The interconnection scheme used for the phases of a four phase converter is shown in Figure 4.

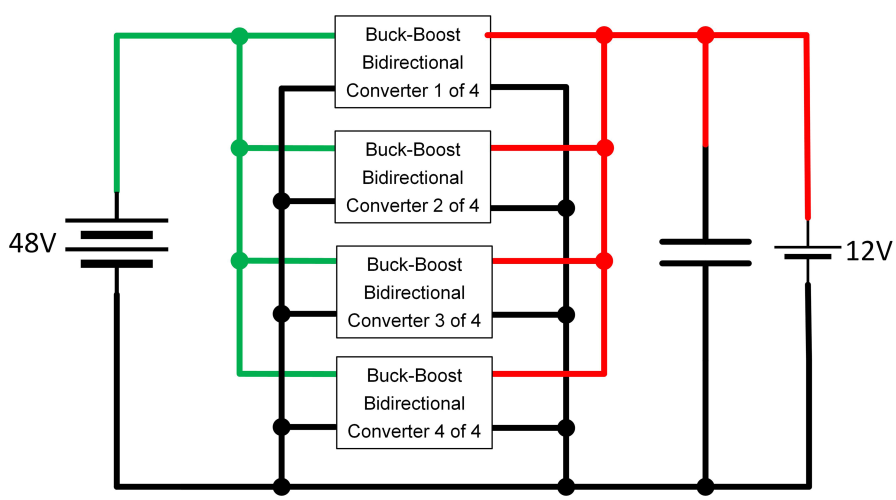

Figure 4. Interleaved Phase Configuration

During typical vehicle operation, the 12 V system has power requirements that fluctuate over time based on the various vehicle operating modes. For some vehicle operating modes, full power may be required, while at other times small amounts of power may be sufficient. In order to improve the overall efficiency of the converter, the interleaved converter can temporally disable phases and, in doing this, the controller can closely match the number of phases that are in operation with the amount of power demanded. When demand is low, multiple phases can be switched off using the battery−disconnect switches. In addition, during these periods of low power demand, with some phases turned off, the converter controller can switch on phases that have previously been off, to evenly distribute the thermal load across all phases.

The load−disconnect switch stages are responsible for electrically connecting and disconnecting each phase from the 12 V battery. They consist of back−to−back power MOSFETs, rated at the phase output current level. These switches may need to be operated continuously and therefore require gate drivers that can operate at 100% on−time.

During some failure modes these MOSFETs must be turned off to disable a failed stage from operating. The corresponding source−disconnect switch must also be disconnected to completely isolate the failed circuitry.

CONVERTER OPERATION

The bi−directional converter has several different modes of operation, based on specific vehicle operating modes. During vehicle start the current for the ISG is drawn from the 48 V battery. If the 48 V battery has insufficient charge the converter will be configured to operate in boost mode, to provide additional starting current from the 12 V battery. It is common for a Li−Ion battery to have poor power performance at cold temperatures and during these times power from the 12 V battery may be required to start the vehicle. In this event, the converter will be configured to deliver current from the 12 V battery to aid the 48 V battery in starting the vehicle. Typically, the engine start/stop functionality will be inhibited until all systems have reached normal operating temperature, at which point normal vehicle re−starts will commence.

During periods when the vehicle is warm and driving, but doesn’t require additional acceleration, the converter will operate in the buck mode. In this mode the converter will be configured to deliver current from the 48 V battery to the 12 V battery. The converter will provide the necessary current to supply all of the 12 V loads as well as provide any required charging of the 12 V battery.

While the vehicle is operating in the normal driving mode and additional acceleration is requested, the converter will be switched into the boost mode where additional current will be delivered to the ISG motor to aid in accelerating the vehicle. Following the acceleration event, the system will return to the normal driving mode, switching the converter into the buck mode. See Table 1. Showing the various vehicle and converter operating modes.

Table 1. OPERATING MODES

Vehicle Mode	Converter Mode	Current Direction
Cold Starting	Boost mode	12 V battery → 48 V battery
Vehicle Acceleration	Boost mode	12 V battery → 48 V battery
Vehicle Driving	Buck mode	48 V battery → 12 V battery

CONVERTER DESIGN

The main circuit components used to realize each stage of this converter are outlined in Table 2.

Table 2. DESIGN REQUIREMENTS

Converter Stage	Components Required
Source−disconnect	− 80 V/100 V trench power MOSFET’s − High−side gate driver
Synchronous buck/boost	− 80 V/100 V trench power MOSFET’s or APM − High−side & low−side gate drive − Power inductor
Current sense amp	− Current sense amplifier − Shunt resistor
Load−disconnect	− 40 V trench power MOSFET’s − High−side gate driver

The semiconductor components used for the design of the source−disconnect stage can be achieved using discrete MOSFETs or an integrated MOSFET power module. 80 V or 100 V Trench MOSFET devices are typically used for the source−disconnect stage. The primary purpose of this stage is to isolate the input of each of the interleaved stages from the other stages as well as the 48 V battery. The back−to−back switch configuration is used to connect and disconnect each phase. The back−to−back configuration is chosen to isolate the circuits from conduction in both directions. Each of these devices must be controlled by a gate driver that has high−side drive capability, since these MOSFETs operate at floating voltage potentials. Once in operation, these devices may need to remain in conduction for extended periods of time, which implies that they must also be capable of 100% on−time conduction.

The buck−boost stage is the heart of the converter. Each one consists of two MOSFET devices connected in a half−bridge configuration connected to the power inductor. These devices are typically 80 V or 100 V trench MOSFET devices. These MOSFETs must be controlled by high−side and low−side gate drivers which may be independently packaged or co−packed into a dual driver IC.

Alternatively this stage can be realized using a highly compact Automotive Power Module (APM), as shown in Figure 5.

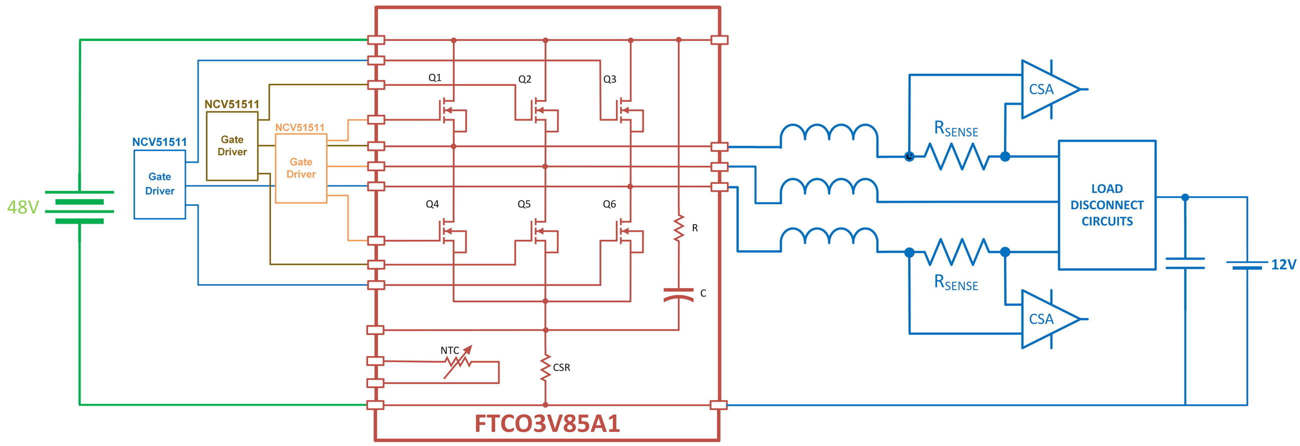

Figure 5. Automotive Power Module Based Design

This **onsemi** integrated power module features: low thermal resistance, low internal electrical resistance and improved EMI performance, in a compact AEC qualified package. In this implementation, the source−disconnect circuits are not used; for individual phase isolation the load−disconnect circuitry can be used.

The main power inductors are designed to store the energy of each of the converter phases. Depending on the current direction, it will deliver the demanded energy to either of the batteries based upon the converter controller commands. The converter controller issues the commands to control the two main switches, which determine the direction of power flow in the converter. For this stage to operate correctly the current must be accurately measured, to properly adjust the main inductor current. The use of a Current Sense Amplifier is ideal for this task, as they are designed to have extremely low error.

The power semiconductor design for each of the load−disconnect stages can be achieved using discrete MOSFETs or an integrated MOSFET power module. 40 V trench MOSFET devices are used for the load−disconnect stages. The primary purpose of this stage is to isolate the output of each of the interleaved phases from the others and from the 12 V battery. The back−to−back switch configuration is used to perform the same isolation functions implemented in the source−disconnect stages. It permits conduction in both directions and also blocks conduction in both directions. These devices must also be controlled by a gate driver device that has high−side drive capability and is capable of 100% on−time operation.

CONVERTER DESIGN USING GaN

With automotive applications demanding ever increasing improvements in both size and efficiency, Wide Band Gap (WBG) devices offer an alternative to the use of standard Silicon devices. Gallium Nitride (GaN) devices offer an attractive alternative for increasing efficiency and reducing size, while potentially decreasing the total system cost.

Since GaN devices significantly reduce switching losses, buck converters using GaN can be switched many times faster than typical Silicon power transistors. Additionally, GaN transistors do not suffer from reverse recovery loss, thus eliminating the generation of large current spikes and power losses during hard−switching transitions.

In addition to size reduction, switching faster can yield other advantages in automotive applications. Using switching frequencies outside the 540 to 1600 kHz AM radio band is necessary to avoid interference with the on−board radio.

The minimization of EMI is critical in automotive applications as the total vehicle needs to pass stringent electrical emission testing before its release. Typically the converter switching frequency is far below the RF radio frequencies, but their harmonics can extend to very high frequencies while still containing sufficient energy to cause interference with reception. Switching at higher frequencies allow the controller the freedom to operate in a manner that permits harmonics to be spaced further apart. This can be accomplished by many different techniques such as: pulse skipping and frequency hopping. The greater efficiency of GaN−based circuitry make high−frequency buck converters a better choice for EMI−sensitive applications.

onsemi is a worldwide manufacturer of WBG power devices, including Silicon Carbide (SiC) and GaN transistors. These devices are capable of supporting new designs that enable power converters with much better efficiency than those created using standard Silicon power switches.

SUMMARY/CONCLUSIONS

With the widespread introduction of many new Mild Hybrid Electric Vehicles, global vehicle manufacturers are betting on these new topologies to have a positive impact on their overall fleet MPG. Each company is measured by a factor called the Corporate Average Fuel Economy (CAFÉ), used to gauge each auto company’s progress at improving their vehicle’s green footprint. A direct consequence of the MHEV proliferation is the increase of the 48 V battery sub−systems, and as long as they retain 12 V electrical components, a 48 V to 12 V converter will be required.

Many different possible topologies for this converter could be envisioned. The bidirectional interleaved synchronous buck−boost converter topology has become the most widespread due to its simplicity and high efficiency. Also, it is chosen for its ability to be designed in multiple interleaved phases, which support its high efficiency over a wide operating range. This is important because the 12 V vehicle loads vary greatly over time and even though the converter needs to function at the maximum load point, it seldom stays there for long. When the loading is light, the converter will shed unnecessary interleaved phases, by use of the disconnect switches to reduce losses and maintain high efficiency.

Therefore, the cost of this converter will be considered a consequence of adding a 48 V battery sub−system to any vehicle. As future vehicle designs move additional system components to the 48 V bus the capacity and cost of the converters may be reduced.

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