

HIGH EFFICIENCY & HIGH PERFORMANCE CONVERTER/INVERTER SYSTEM
CONFIGURATIONS FOR HEV/EV TRACTION DRIVES

By

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ABSTRACT

HIGH EFFICIENCY & HIGH PERFORMANCE CONVERTER/INVERTER SYSTEM CONFIGURATIONS FOR HEV/EV TRACTION DRIVES

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Abstract—Hybrid and electric vehicles are becoming increasingly important as the cost of available resources increase and as pollution and greenhouse gasses become more pressing concerns. Hybrid and electric vehicles offer a means to increase efficiency and decrease pollution and greenhouse gasses.

Whether the hybrid system is a series or series/parallel system, the vehicles discussed in this work use an internal combustion engine (ICE), an AC electric generator, a passive/active rectifier/inverter, a power storage system, a traction motor inverter, and a traction motor/brake. The value of the hybrid vehicle comes from its increased efficiencies. The hybrid system decouples the ICE's power and speed from that of the vehicle. This decoupling is accomplished by replacing the traditional mechanical or hydro mechanical transmission with power electronics and energy storage facilities. This decoupling allows ICE operation at its most efficient power versus speed point. During normal operation, the energy storage system can be used to handle the dynamic loads and the internal combustion engine can handle the steady state loading. This hybrid system also recaptures braking energy which is lost with conventional vehicle systems. The power electronics facilitate the process via control of power flow, battery management, motor control and generator control.

The existing hybrid vehicle power electronics topologies are discussed which include the traditional back to back voltage source inverter to voltage source inverter configuration as well as the newer back to back Z-Source type configurations. Each of these designs has specific operation modes, control methods and features that are analyzed and discussed in this document. The advantages and disadvantages of each are discussed and this will form a basis upon which the new high efficiency designs proposed in this work can be compared.

Finally, several new higher efficiency topologies are proposed and the basic features and functionality of these proposed configurations are discussed. These new configurations are then analyzed and quantified in terms of calculated efficiency.

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TABLE OF CONTENTS

LIST OF FIGURES	VIII
KEYS TO SYMBOLS OR ABBREVIATIONS	XII
1. INTRODUCTION	1
1.2 Conventional Vehicles	2
1.3 Alternative Vehicles	3
1.4 Hybrid Vehicles	5
1.4.1 Series Hybrid Vehicle	7
1.4.2 Parallel Hybrid Vehicle	8
1.4.3 Series-Parallel Hybrid Vehicle	10
1.5 Fuel Cell Vehicles	12
1.6 Outline of Thesis	13
2. REVIEW OF EXISTING HYBRID ELECTRIC VEHICLE POWER ELECTRONICS TOPOLOGIES AND THEIR OPERATING PRINCIPLES	17
3. EVALUATION OF MAJOR HEV COMPONENTS AND OVERALL OPERATION OF HEV	29
3.1 Characteristics of the Internal Combustion Engine (ICE)	31
3.2 Characteristics of the Hybrid Battery Pack	33
3.2.1 Comparison of the high voltage battery vs. the low voltage battery. High voltage battery option.	34
3.2.2 Comparison of the high voltage battery vs. the low voltage battery. Low voltage battery with DC/DC converter option.	37
3.2.3 Summary of High Voltage Battery Option vs. Low Voltage Battery Option	38
3.3 Characteristics of Inverters and Converters	38
3.4 Traction Motor Operating Conditions	41
3.5 Summary of Hybrid Major Components	43
4. PRESENTATION AND BRIEF ANALYSIS OF PROPOSED TOPOLOGIES	46
4.1 VSI / VSI with Conventional Mid-Link DC / DC Converter	47
4.2 VSI / VSI with “H” Bridge Coupled Battery Pack	49
4.3 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter	51
4.4 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter	52

4.5 VSI / VSI Structure, LV Battery, DC-Link with Integrated Magnetic Boost Converter Using Open Circuit Zero States of Inverter Phase Legs	54
4.6 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converter	59
4.7 Back to Back Current Fed Quasi-Z-Source Inverters, LV Battery	61
4.8 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery	62
4.9 Summary of proposed topologies	64
5. LOSS ANALYSIS OF SELECTED TOPOLOGIES	65
5.1 Base Line:	65
5.1.1 Evaluation of Efficiency of the topologies.	65
5.1.2 Experimental Results	71
5.1.3 Base Line Continued	79
5.2 Proposed Topologies	82
5.2.1 VSI / VSI with Conventional Mid-Link DC / DC Boost Converters	83
5.2.2 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter	85
5.2.3 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter	87
5.2.4 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converters	88
5.2.5 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery	89
5.2.6 Back to Back Current Fed Quasi-Z-Source Inverter, LV Battery	91
5.3 Conclusion	104
6. FUTURE WORK	110
REFERENCES	112

LIST OF FIGURES

FIGURE 1 TYPICAL INTERNAL COMBUSTION ENGINE (ICE) VEHICLE	3
FIGURE 2 TYPICAL ELECTRIC VEHICLE (EV)	4
FIGURE 3 TYPICAL SERIES HEV	7
FIGURE 4 TYPICAL PARALLEL HEV	10
FIGURE 5 TYPICAL SERIES-PARALLEL HEV [5]	11
FIGURE 6 TYPICAL SERIES-PARALLEL HEV WITH PLANETARY GEAR SET [5]	12
FIGURE 7 TYPICAL FUEL CELL VEHICLE	13
FIGURE 8 TRADITIONAL INPUT RECTIFIER/VSI TO OUTPUT VSI	21
FIGURE 9 TRADITIONAL INPUT RECTIFIER/VSI TO OUTPUT VSI WITH	22
FIGURE 10 INPUT RECTIFIER/VSI TO OUTPUT CSI WITH Z-SOURCE IMPEDANCE	24
FIGURE 11 INPUT RECTIFIER/CSI TO OUTPUT VSI WITH Z-SOURCE IMPEDANCE	26
FIGURE 12 INPUT RECTIFIER/VSI TO OUTPUT CSI WITH Z-SOURCE IMPEDANCE	28
FIGURE 13 SERIES HYBRID ELECTRIC CONFIGURATION	30
FIGURE 14 TYPICAL TORQUE VS. SPEED CURVES OF A DIESEL ICE	32
FIGURE 15 TRADITIONAL BACK TO BACK VSI / VSI HYBRID TOPOLOGY	33
FIGURE 16 SERIES COMBINATION OF BATTERY CELLS	36
FIGURE 17 IGBT MODULE USED IN INVERTERS AND CONVERTERS	39
FIGURE 18 EPA URBAN DYNAMOMETER DRIVING SCHEDULE (UDDS)	42
FIGURE 19 TRADITIONAL BACK TO BACK VSI / VSI HYBRID TOPOLOGY	43
FIGURE 20 VSI / VSI WITH CONVENTIONAL MID-LINK DC / DC CONVERTER	47
FIGURE 21 VSI / VSI WITH CONVENTIONAL MID-LINK DC / DC CONVERTER.	48
FIGURE 22 VSI TO VSI TOPOLOGY WITH AN “H” BRIDGE COUPLING THE BATTERY	49

FIGURE 23 VSI TO VSI TOPOLOGY WITH AN “H” BRIDGE COUPLING THE BATTERY PACK TO THE DC-LINK.....	50
FIGURE 24 VSI / VSI STRUCTURE, LV BATTERY WITH BOOST CONVERTER, & DC-LINK WITH BUCK CONVERTER.....	51
FIGURE 25 VSI / VSI STRUCTURE, LV BATTERY WITH BOOST CONVERTER, & DC-LINK WITH BUCK CONVERTER.....	52
FIGURE 26 VSI / VSI STRUCTURE, LV BATTERY WITH BUCK-BOOST CONVERTER, & DC-LINK WITH BUCK CONVERTER.....	52
FIGURE 27 VSI / VSI STRUCTURE, LV BATTERY WITH BUCK-BOOST CONVERTER, & DC-LINK WITH BUCK CONVERTER.....	53
FIGURE 28 VSI / VSI STRUCTURE, LV BATTERY, DC-LINK WITH INTEGRATED MAGNETIC BOOST CONVERTER	54
FIGURE 29 VSI / VSI STRUCTURE, LV BATTERY, DC-LINK WITH INTEGRATED MAGNETIC BOOST CONVERTER	56
FIGURE 30 INVERTER SWITCHING STATE, DC-LINK VOLTAGE, AND BACK EMF	57
FIGURE 31. SWITCH STATES AND DC-LINK VOLTAGE.....	58
FIGURE 32 VSI / VSI STRUCTURE, LV BATTERY, DC-LINK WITH BI-DIRECTIONAL BUCK	59
FIGURE 33 VSI / VSI STRUCTURE, LV BATTERY, DC-LINK WITH BI-DIRECTIONAL BUCK	60
FIGURE 34 BACK TO BACK CURRENT FED QUASI-Z-SOURCE INVERTERS, LV BATTERY ..	61
FIGURE 35 BACK TO BACK CURRENT FED QUASI-Z-SOURCE INVERTERS, LV BATTERY. .	61
FIGURE 36 BACK TO BACK VOLTAGE FED QUASI-Z-SOURCE INVERTERS, LV BATTERY ..	62
FIGURE 37 BACK TO BACK VOLTAGE FED QUASI-Z-SOURCE INVERTERS, LV BATTERY. .	63
FIGURE 38. VOLTAGE AND CURRENT WAVEFORMS OF A TYPICAL SEMICONDUCTOR SWITCHING DEVICE	67
FIGURE 39. EXPERIMENTAL SET UP SCHEMATIC DIAGRAM	72
FIGURE 40 EXPERIMENTAL SETUP	73
FIGURE 41 AMPLITUDE MODULATED ROTOR POSITION SIGNALS.	74

FIGURE 42 AMPLITUDE MODULATED ROTOR POSITION SIGNALS	75
FIGURE 43 CHASSIS DYNO. USED TO OBTAIN EXPERIMENTAL RESULTS.....	76
FIGURE 44 EXPERIMENTAL SETUP.....	77
FIGURE 45 MORE OF THE EXPERIMENTAL SETUP.....	78
FIGURE 46 EXPERIMENTAL RESULTS SHOWING FOUR OPERATING POINTS	78
FIGURE 47. POWER LOSS CURVES FOR THE TRADITIONAL BACK TO BACK VSI/VSI.....	82
FIGURE 48 BACK TO BACK VSI TO VSI WITH BOOST CONVERTERS IN THE DC-LINK	83
FIGURE 49 LOSS GRAPHS (A, B, AND C) FOR THE BACK TO BACK VSI TO VSI WITH BOOST CONVERTERS IN THE DC-LINK	83
FIGURE 50 BACK TO BACK VSI / VSI TOPOLOGY WITH BATTERY BOOST CONVERTER AND TI DC-LINK BUCK CONVERTER.	85
FIGURE 51 LOSS GRAPHS (A, B AND C) FOR THE BACK TO BACK VSI / VSI TOPOLOGY	85
FIGURE 52 BACK TO BACK VSI / VSI TOPOLOGY WITH BATTERY BUCK-BOOST CONVERTER	87
FIGURE 53 LOSS GRAPHS UNDER SCENARIO ONE CONDITIONS (GENERATOR AT 50kW).....	87
FIGURE 54 BACK TO BACK VSI / VSI TOPOLOGY WITH GI BI-DIRECTIONAL BUCK-BOOST. .	88
FIGURE 55 LOSS GRAPHS UNDER SCENARIO ONE CONDITIONS (GENERATOR AT 50kW).....	88
FIGURE 56 BACK TO BACK VOLTAGE FED QUASI Z SOURCE INVERTER TOPOLOGY.	89
FIGURE 57 LOSS GRAPHS (A, B, AND C) FOR THE BACK TO BACK VOLTAGE FED QUASI Z SOURCE INVERTER TOPOLOGY	89
FIGURE 58 BACK TO BACK CURRENT FED QUASI Z SOURCE INVERTER TOPOLOGY.	91
FIGURE 59. POWER LOSS COMPARISONS BETWEEN THE TRADITIONAL TOPOLOGY AND	91
FIGURE 60. OPERATIONAL STATES (A, B, AND C) OF THE CF-QZSI [27]	94
FIGURE 61. V_{OUT}/V_{IN} VS. ACTIVE DUTY CYCLE. [27].....	96
FIGURE 62. GENERATOR END OF THE BACK TO BACK CF-QZSI TOPOLOGY	98

FIGURE 63. (A) AND (B) GI VOLTAGE IS BEING BUCKED FROM THE GI LEVEL	99
FIGURE 64. THE SWITCHING STATES USED TO START THE DIESEL ICE.....	100
FIGURE 65 COMPARATIVE POWER LOSS GRAPHS FOR THE TRADITIONAL,	106

KEYS TO SYMBOLS OR ABBREVIATIONS

ac voltage at the generator/starter motor - Line to Line (V_{G-LL})

ac voltage at the generator/starter motor - peak ($\hat{V}_G$)

ac voltage at the generator/starter motor - RMS (V_G)

ac voltage at the traction motor - Line to Line (V_{TM-LL})

ac voltage at the traction motor - peak ($\hat{V}_{TM}$)

ac voltage at the traction motor - RMS (V_{TM})

Acceleration of automobile (a_a)

Acceleration of bus (a_b)

amperes (A)

Angular velocity (ω)

Average Line Current (I_{AV} or I_{av})

Battery terminal voltage (V_{BAT})

Battery Voltage (V_{BATT})

Boost factor (B)

Buck–boost factor (B_B)

Capacitor voltage (V_C)

Collector current (I_C)

Conditional probability of a short circuit failure (p)

Conditional probability of an open circuit failure (q)

Constant power speed ratio (CPSR)

Corporate Average Fuel Economy (CAFE)

Cumulative distribution function of time to failure for a reliability study ($F(t)$)

Current Fed Z-Source Inverter (CF-ZSI)

Current Source Inverter (CSI)

DC bus voltage (V_{cc})

DC voltage (V_{dc})

DC-Link voltage on the Generator Inverter End (V_{DC_GI})

DC-Link voltage on the Traction Inverter End (V_{DC_TI})

Diode conduction loss (P_d)

Duty cycle of switching device (D)

Electric vehicle (EV)

Electro Magnetic Interference (EMI)

Environmental Protection Agency (EPA)

Filter voltage (V_F)

Force of acceleration of a bus (F_b)

Force of acceleration of an automobile (F_a)

Fuel cell (FC)

Fuel cell hybrid electric vehicle (FC HEV)

Fuel cell vehicle (FCV)

Generator Inverter (GI)

Generator Power, Three Phase ($P_{3\phi}$)

Generator Voltage (V_G)

Hybrid electric vehicle (HEV)

Hybrid vehicle (HV)

IGBT conduction loss (P_i)

Insulated Gate Bi-Polar Junction Transistor Module (IGBT)

Internal combustion engine (ICE)

Kilowatt (kW)

Kilowatt hour (kWhr)

Line to line voltage (V_{LL})

Mass of automobile (m_a)

Mass of buss (m_b)

Maximum collector current (I_{cM})

Modulation index (M)

Modulation index (M)

Newton Meter (Nm)

number of components in series in a reliability study (n)

number of parallel paths in a reliability study (m)

Open Circuit Zero Switching Period (T_{OCZ}) or (T_1)

Open Circuit Zero switching state (OCZ)

Peak Line Current ($\hat{I}$)

Phase A Lower switch gate control signal (S_{an})

Phase A upper switch gate control signal (S_{ap})

Phase A voltage reference (V_{a*})

Phase angle between phase voltage and line current (Θ)

Phase B Lower switch gate control signal (S_{bn})

Phase B upper switch gate control signal (S_{bp})

Phase B voltage reference (V_{b*})

Phase C Lower switch gate control signal (S_{cn})

Phase C upper switch gate control signal (S_{cp})

Phase C voltage reference (V_{c*})

Pulse width modulation (PWM)

Rated collector current (I_{cN})

Rated collector to emitter voltage (V_{ceN})

Rated diode forward voltage (V_{FN})

Rated fall time (t_{fN})

Rated recovery charge (Q_{rm})

Rated recovery time (t_{rN})

Rated rise time (t_{rN})

Reliability as a function of time ($R(t)$)

Reverse Blocking Insulated Gate Bi-Polar Junction Transistor Module (RB-IGBT)

Reverse recovery loss of the diode (P_{rr})

Revolutions Per Minute (rpm)

Series Hybrid Electric Vehicle (SHEV)

Shoot-through duty cycle (D_0)

Short Circuit Zero Switching Period (T_{SCZ})

Sinusoidal pulse width modulation (SPWM)

State of charge (SOC)

Switching cycle interval (T)

Switching Device Power (SDP)

Switching Device Power Ratio (SDPR)

Switching frequency (F_s)

Threshold collector emitter voltage (V_{co})

Threshold diode forward voltage (V_{Fo})

Time during shoot through (T_0)

Torque (τ)

Traction Inverter (TI)

Traction Motor Power, Three Phase ($P_{3\phi_TM}$)

Traction Motor Voltage (V_m)

Turn off loss of the IGBT (P_{off})

Turn on loss of the IGBT (P_{on})

Upper shoot-through envelope (V_p)

Upper shoot-through envelope reference signal (V_{pref})

Urban Dynamometer Driving Schedule (UDDS)

Voltage across filter (V_F)

Voltage Fed Z-Source Inverter (VF-ZSI)

Voltage gain (M_B)

Voltage line to line (V_{LL})

Voltage of battery (V_{BATT}) or (V_{batt})

Voltage Source Inverter (VSI)

Wide open or full throttle (WOT)

Zero emission vehicle (ZEV)

Z-Source Inductor Current (I_{LZ})

Z-Source Inverter (ZSI)

1. INTRODUCTION

Alternatively powered vehicles are becoming of great importance. Several factors are causing the need for change from traditional vehicles. As the population of the planet continues to grow, and as the industrialization of these populations continue to grow, the rate of depletion of traditional fuel sources (fossil fuels – oil, and coal primarily) is also increasing. Along with this increased global demand for power comes the increased pollution from consuming fuels. Both the decreasing supply of fossil fuels and the increasing level of pollutants in our environment are becoming very significant concerns. As a result, there is a growing need to search for ways in which these problems may be reduced or solved. Both alternative fuels and ways to increase efficiency in the use of fuels are being sought after. One such approach to increase efficiency is the development of hybrid and electrical vehicles which are much more fuel efficient and which produce a smaller amount of pollutants. This introduction will provide a discussion of traditional vehicles, electric vehicles, fuel cell vehicles, and hybrid vehicles. Because an understanding of the hybrid electric vehicle and electric vehicle is necessary to understand how the higher efficiency topologies achieve their greater efficiency performance, a brief discussion of hybrid and electric vehicle types follows.

1.2 Conventional Vehicles

The tradition of fuel powered vehicles started in 1769 with a self-propelled military tractor invented by the French engineer and mechanic, Nicolas Joseph Cugnot (1725-1804). Much before this date, conceptual designs had been made by both Leonardo Da Vinci and Isaac Newton.[1] In 1823, Samuel Brown patented the first internal combustion engine to be applied industrially. It was compression-less and based on the "Leonardo cycle," In 1838, a patent was granted to William Barnet (English) for an engine using in-cylinder compression. In 1854, the Italians Eugenio Barsanti and Felice Matteucci patented the first working efficient internal combustion engine in London but did not go into production with it. It was similar in concept to the successful Otto Langen indirect engine, but not so well worked out in detail[2]. Various fuels were used over these years. By far the most prevalent designs today use gasoline or diesel fuel. The typical road vehicle in use today is based upon a standard platform. That is a gasoline or diesel fueled internal combustion compression engine. The engine is coupled to the remainder of the drive train through a multiple gear ratio transmission. From the transmission, power is delivered to the drive wheels through a drive shaft/s and a differential gear box. The engines are of the cylindrical compression type, and the transmission usually has three or more discrete gear ratios. The function of the differential gear box is to allow one of the drive wheels to rotate at a different speed than the other drive wheel while both are delivering power to the road. Each of these drive train components is mechanical. See Figure 1 for a schematic of the typical conventional vehicle.

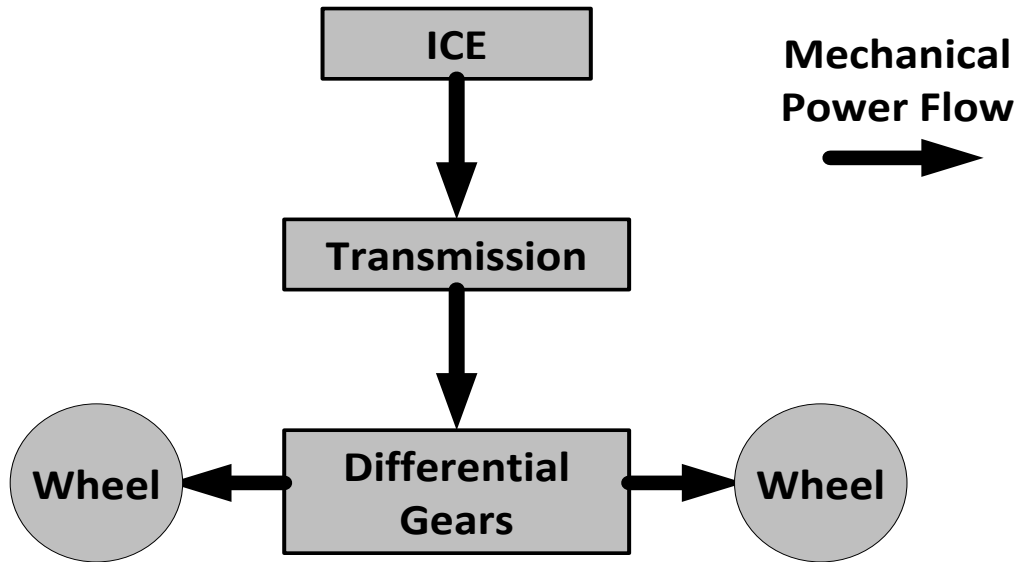


Figure 1 Typical Internal Combustion Engine (ICE) Vehicle

Hybrid vehicles use some combination of these mechanical components as well as electrical components to drive the vehicle.

1.3 Alternative Vehicles

Various countries and governments across the globe are trying to foster the development of alternative vehicles that mitigate some of these concerns. Alternatives are necessary to eventually create vehicles that do not further deplete crude oil reserves and that produce pollutants at a much lower rate. The population of the world continues to grow, more nations are becoming industrialized, and burning of fossil fuels is believed to contribute to global warming. There are many reasons to turn to alternatives that would alleviate some or all of these concerns. One such alternative is the electric vehicle (EV). This vehicle does not have an internal combustion engine and does not burn any fuels on

board. Its power is usually received from the electric utility and stored in batteries that are on board the vehicle.

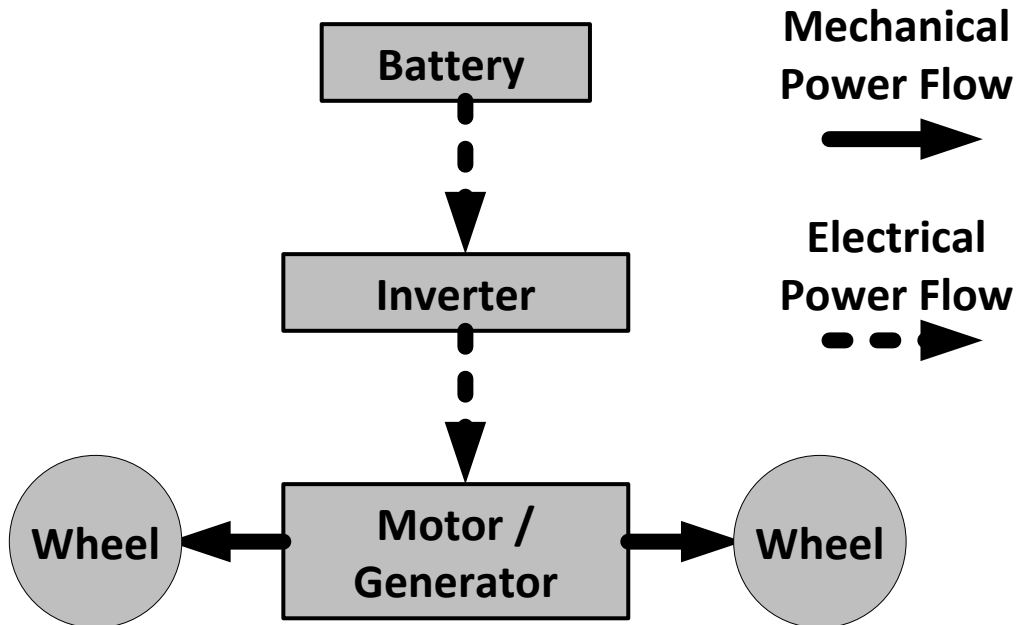


Figure 2 Typical Electric Vehicle (EV)

The stored power is then applied to electric motors to drive the vehicle rather than using an ICE. This type of vehicle is very efficient as compared to conventional vehicles. Presently, the fuel cost per mile (cost per kilo-watt hour (kWhr)) is about 3 cents per mile as compared to 14 cents per mile for gasoline in the conventional automobile. One of the main advantages of the EV is that it is a zero emission vehicle (ZEV). Although there is some pollution created when the electricity is generated at the utility power plant, this is insignificant compared to emissions from conventional ICE vehicles. EVs are also very efficient when compared to conventional ICE vehicles; only about 20% of the chemical

energy in gasoline is converted into work at the wheels of an ICE vehicle, 75% or more of the energy from a battery reaches the wheels of an EV [3]. EVs also provide strong performance, due to the fact that electric motors provide nearly peak torque even at low speeds. Cost, performance, and convenience of an EV all depend on the battery. There are several types of batteries commonly used in EVs, advanced lead-acid batteries, nickel-metal hydride, and lithium polymer batteries [3]. The drawback to this type of vehicle is that it takes more time to recharge the batteries and recharging stations are not yet commonly available. Because of the limited storage capacity of the batteries, the range of these vehicles is also more limited.

1.4 Hybrid Vehicles

Hybrid vehicles (HV) are growing in popularity for their fuel efficiency and lower emissions. Fuel costs are increasing and the world's fuel reserves are continuing to decrease. Since the world's supply of crude oil is based in just a few countries, a nation's dependence on oil also makes it dependent upon the oil producing nation. Also, pollution issues are increasing in weight. These are the main reasons why the demand for HVs is increasing and why governments are encouraging the sales and development of these vehicles.

A HV is any vehicle that combines two or more sources of power to propel the vehicle. Some of the first HVs were busses, trains, and submarines. Hybrid methods are now being applied to passenger cars, small trucks, and industrial vehicles such as excavators and busses. There are three main configurations of HVs. They are the Series Hybrid, Parallel Hybrid, and Series/Parallel Hybrid. They are summarized below.

A common type of hybrid electric vehicle (HEV) combines the energy storage of the EV with an energy source such as an ICE. HEVs have higher efficiency levels due to regenerative braking, and due to their ability to control power from the ICE. By controlling the power flow, it is possible to utilize the most efficient points of operation. Regenerative braking takes advantage of the concept that energy can neither be created nor destroyed – it just changes form. The conventional vehicle converts the kinetic energy of the moving vehicle into heat energy when the brakes are applied to slow the vehicle. This radiated heat is lost to the atmosphere. The HEV converts this inertia into electrical energy by using the traction motor as an electric generator. The production of electrical energy by the generator also produces a resistive torque against the free rotation of the drive wheels which slows the vehicle. This electrical energy is stored as potential energy in the vehicle's battery bank and or ultra-capacitors. In this way, energy that would have been wasted is saved for later use. Also, the HEV can use a smaller ICE. The ICE only needs to supply the consistent steady state load while the battery and electric motor can provide power for the dynamic load. Some examples of the dynamic load would be the additional power needed to accelerate and to climb hills. The smaller ICE uses less fuel than the larger engines do. The smaller engine requires less fuel into the smaller cylinders to achieve the correct air to fuel ratios and expends less energy pumping the air and combustion gases in and out of the cylinders. Also, an ICE has moving parts which involve friction. The smaller parts have less surface friction. Also, the engines have linear reciprocating motion components which must undergo four accelerations for each crank shaft revolution. Obviously, the lower mass components require less energy.

1.4.1 Series Hybrid Vehicle

The series HEV delivers all of the power to the drive wheels via electric power. None of the power is delivered with direct mechanical connections. For example, a typical configuration uses an ICE connected to a generator. The generator is connected to the traction motor through an electric power inverter and conductors. The power inverter is usually connected to power storage devices such as batteries and or ultra-capacitors. See Figure 3.

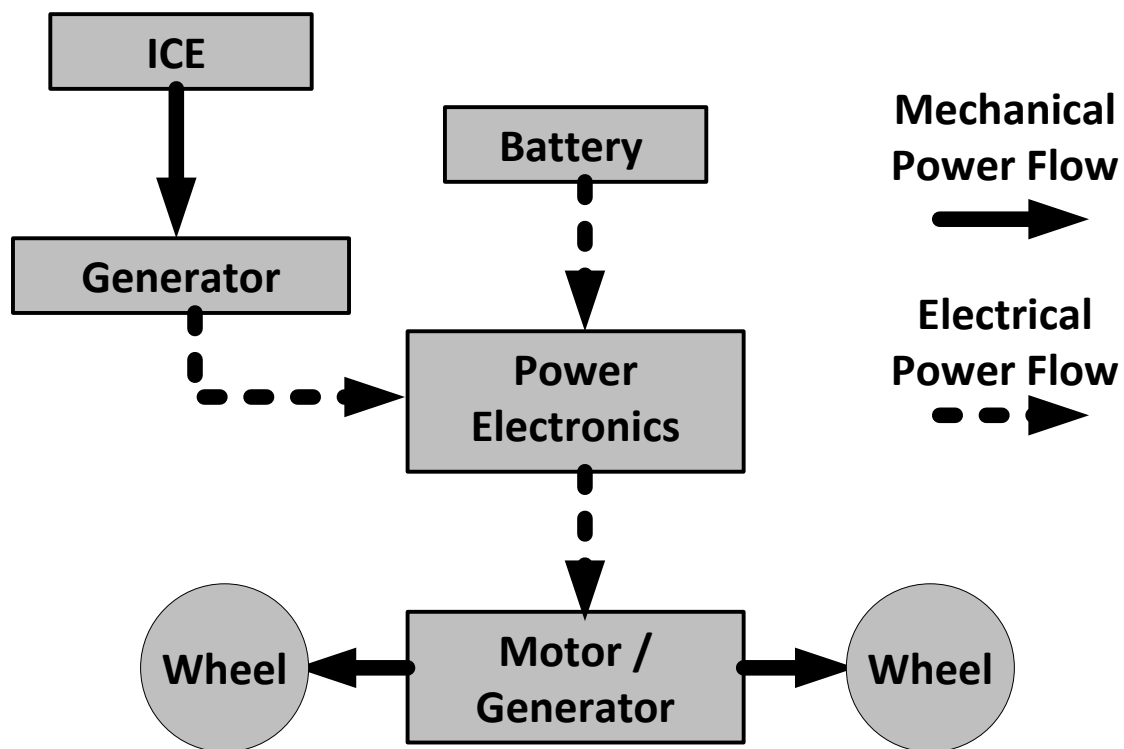


Figure 3 Typical Series HEV

The series HEV uses an ICE which runs for extended periods of time at maximum efficiency, and can shut off when the batteries reach a selected state of charge (SOC). The ICE is then allowed to operate at the average required power level and the

batteries will accept power when this average exceeds instantaneous traction power demand. The battery likewise provides power when the traction power required exceeds the ICE's average power provided.

In the series HEV configuration the electric motors and power electronics must be sized for the whole load whereas the parallel case can use a smaller inverter and motor. Still, the ICE is smaller than that in the conventional vehicle and is comparable to that of the parallel case. Also, this design does not require the additional equipment needed for the parallel case. In higher power applications (busses, freight trains, subway trains), this is a very effective design application.

The series HEV suffers due to the number of energy conversions. The engine converts petroleum potential energy to kinetic energy (rotational motion); the generator converts this kinetic energy to electrical energy. The electrical energy is then converted to chemical energy in the battery and to mechanical (kinetic energy) in the traction motor. However, the series HEV does not require a lossy hydro mechanical transmission. Also, batteries have limited life expectancy. New battery technology has made great improvements with this and there are several batteries that have long life periods when the battery state of charge (SOC) is maintained within a fairly narrow band and when the charge and discharge rates are maintained within specified limits [3].

1.4.2 Parallel Hybrid Vehicle

The parallel hybrid vehicle has two power flow paths. One is mechanical from the ICE to the wheels, and the other is electrical from the generator and batteries to the electric

motor and then mechanically to the wheels. The battery is recharged from regenerative braking and by operating the ICE at a power level in excess of the instantaneous traction power demand. This excess power is delivered to the batteries through a gearing mechanism, to a motor (being operated as a generator), to the power inverter/converter and then to the battery. The main advantages of this system are that both the engine and the motor size can be minimized since both can deliver power to the wheels at the same time to accommodate the peak load requirements. Also, there are potentially less energy conversions for the mechanical power flow path. On the other hand this system typically utilizes a hydro mechanical transmission which has losses, and the control is more complicated than the series HEV [3].

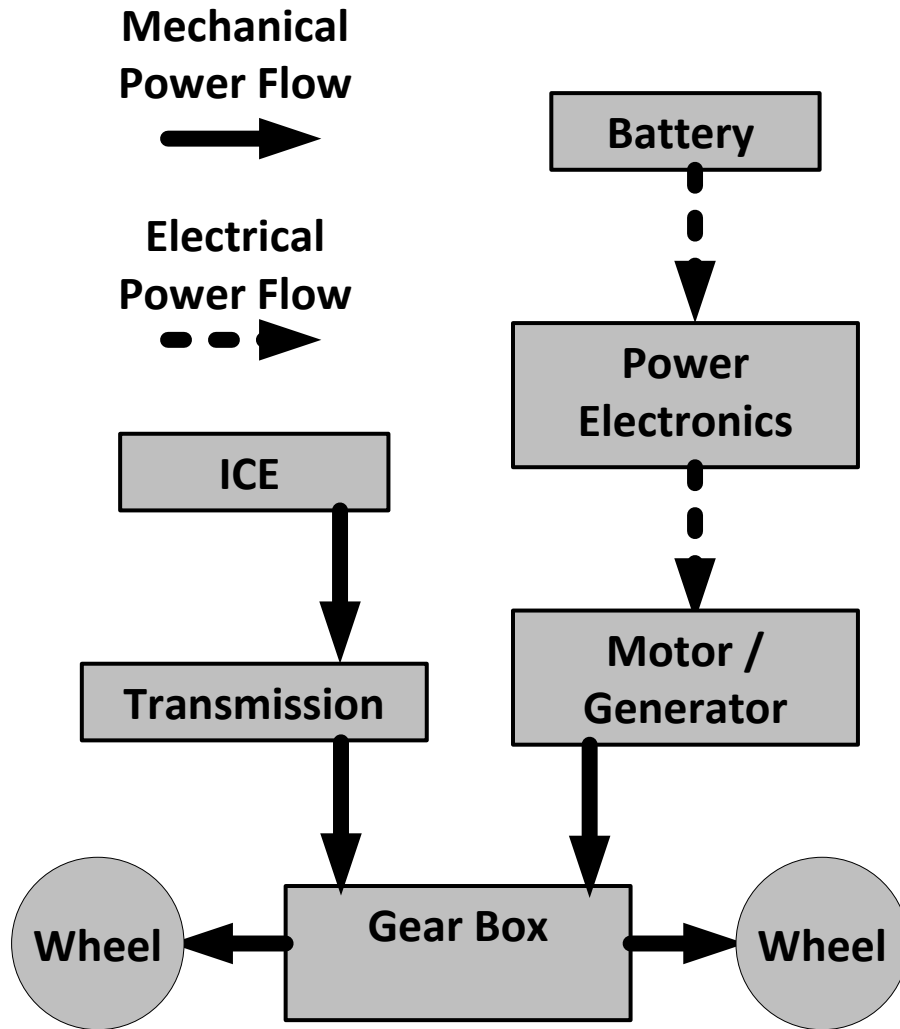


Figure 4 Typical Parallel HEV

1.4.3 Series-Parallel Hybrid Vehicle

The series-parallel HEV combines features from both of the preceding cases. This system can operate in series mechanical mode, series electrical mode, or any combined ratio of the two. As a result, the control system can choose the most advantageous operation mode for the given circumstances.

Figure 5 shows a power flow diagram for a series-parallel hybrid. Also notice the

planetary gear component in this figure. This is also a very significant part of the efficiency of the design. The planetary gears (see Figure 6 for a diagram) deliver power from the ICE to the wheels or to the generator. It also couples power transfer to or from the generator. The generator is an instrumental part of this control. The generator is used to create either positive or negative torque so that the desired gear ratio between the ICE and vehicle wheels is achieved. As a result of the ideal gear ratio, the ICE is continuously operated at its most efficient point for the given power demand. Also, the planetary gear system does not use lossy hydraulic torque converters as the conventional vehicle does.

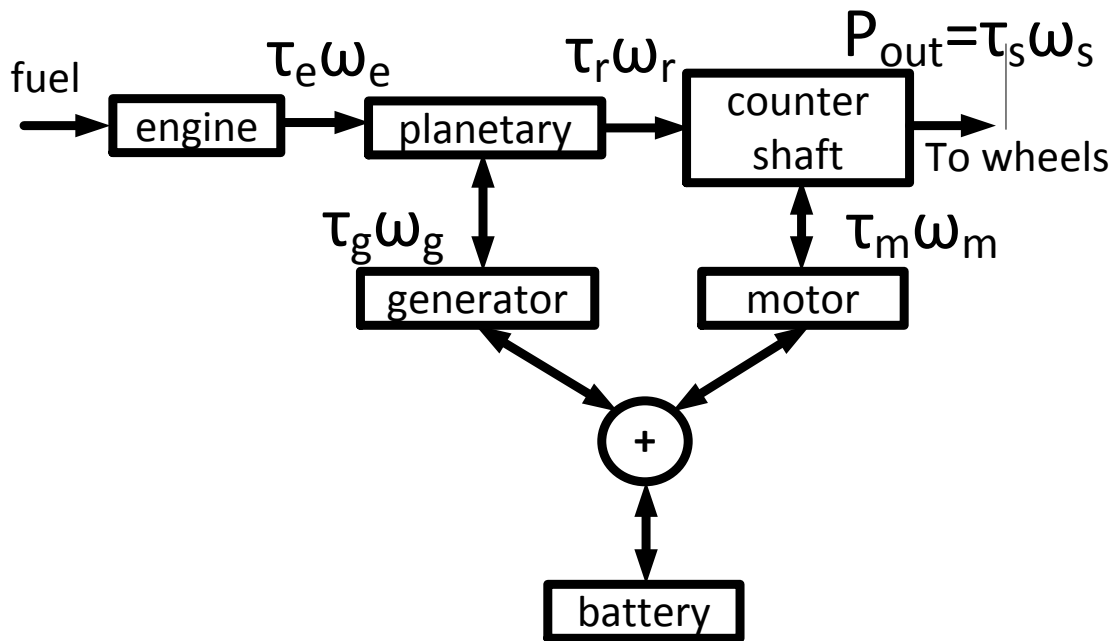


Figure 5 Typical Series-Parallel HEV [5]

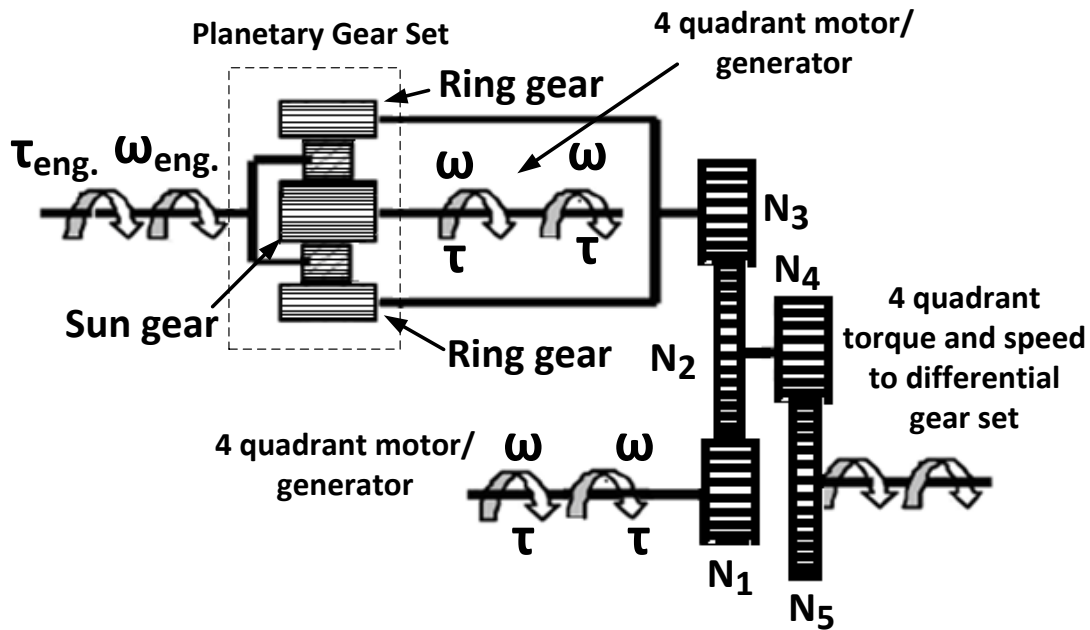


Figure 6 Typical Series-Parallel HEV with Planetary Gear Set [5]

This system benefits from the reduced size ICE, generator, power inverter, and traction motor due to its parallel functionality. Also, the operating system is able to select the most advantageous operation mode for the given circumstances.

1.5 Fuel Cell Vehicles

Fuel cell vehicles (FCV) are still being developed and have not yet achieved commercial production. However, this type of vehicle offers a great deal of benefits in terms of efficiency, and very low emissions. Its environmental impact is similar to that of an EV, yet the FCV has a large range comparable to the conventional EV. The FCV utilizes fuels such as hydrogen, methanol, or gasoline to produce electrical power without combustion. The waste product of the reaction is typically H_2O and CO_2 . The drive train of a FCV thus becomes: Fuel Cell, Inverter, and Traction Motor. Most designs will likely

include a battery as well. The typical fuel cell does not have the ability to respond quickly to power demand changes. Therefore, the fuel cell can be used to supply average power and the battery can be used to supply or absorb the difference between average power and instantaneous power. Adding regenerative braking to the FCV makes the design very fuel efficient. Also, the infrastructure for these fuels does not yet exist. Below is a diagram of the FCV structure.

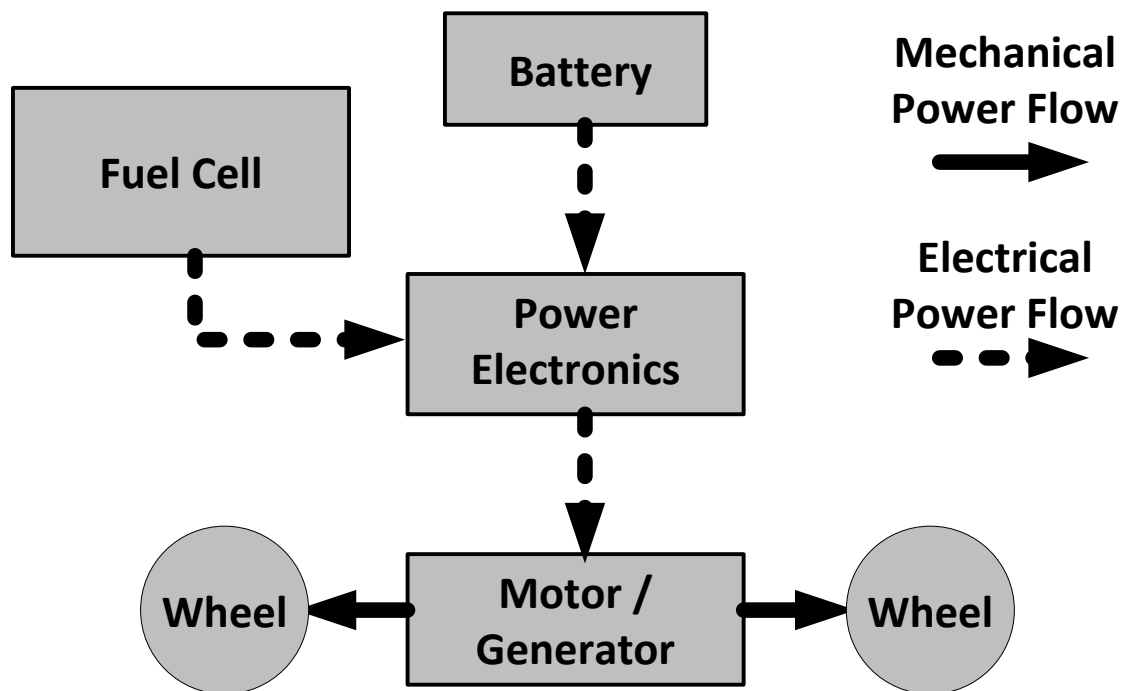


Figure 7 Typical Fuel Cell Vehicle

1.6 Outline of Thesis

The goal of this research is to review the operational characteristics of the major components of the HEV, investigate the conditions under which they operate as well as the overall operating conditions of the overall vehicle with the hope of finding

operational modes or systems that could then be devised to achieve greater efficiency than presently existing technology. The traction drive system will deliver power to and from the ICE via a generator/starter motor and it will deliver power to and from the traction motor/generator. This system will also include interface and control of storage batteries.

Chapter 2: Reviews the current HEV power electronics technologies, and their operating principles. The hybrid operational modes are briefly discussed. These are the mode of operation that a hybrid vehicle must be able to achieve in order to be considered effective. Finally, five existing hybrid vehicle topologies are shown.

Chapter 3: Discusses the major components of the hybrid vehicle system. Specifically, these are the internal combustion engine, permanent magnet alternating current motors / generators, battery packs, DC to AC inverters, DC to DC converter, and the vehicle itself. It is the characteristics of these components that present operating constraints of which the new proposed solutions must abide. However, it is these same constraints that are herein exploited to achieve new and higher efficiency topologies.

3.1 Internal Combustion Engine

3.2 Hybrid Battery Pack

3.3 Inverters and Converters

3.4 Traction Motor and vehicle operating conditions

3.5 Summary of characteristics and presentation of the generator inverter to traction inverter decoupled voltage concept.

Chapter 4: Presents several new topologies the purpose of which is to employ voltage decoupling and thereby reap greater efficiencies. Each topology to be studied in this work is presented in this section along with a brief illustration of power flow through the topology.

4.1 VSI / VSI with mid-link conventional DC/DC converter.

4.2 VSI / VSI with “H” bridge coupled battery stack.

4.3 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter.

4.4 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter.

4.5 VSI / VSI Structure, LV Battery, DC-Link with Integrated Magnetic Boost Converter Using Open Circuit Zero States of Inverter Phase Legs.

4.6 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converter.

4.7 Back to Back Current Fed Quasi-Z-Source Inverters, LV Battery.

4.8 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery.

4.9 Summary of proposed topologies.

Chapter 5: Presents the above topologies which were functional and analyzes their power losses comparing them to the traditional topology. Before this can be done however, the conditions, components, and operating conditions of the analysis are described. Experimental results are presented to confirm the voltage decoupling concept

and to verify the accuracy of the calculations.

5.1 Development of the base line.

5.2 Proposed Topologies

5.3 Conclusions

Chapter 6: The work and results presented in this writing have uncovered yet additional ways in which hybrid vehicles can be further improved. Chapter six suggests some future work toward this extent that can begin where this work ends.

2. REVIEW OF EXISTING HYBRID ELECTRIC VEHICLE POWER ELECTRONICS TOPOLOGIES AND THEIR OPERATING PRINCIPLES

The purpose of this thesis is to investigate traction drive systems for a series hybrid electric bus. The purpose of the power electronics is to control the flow of power from or to the ICE's generator, to or from the batteries, and to or from the traction motor. The voltage must be managed in terms of ac frequency and magnitude. The amount of power flow to or from the system batteries must be managed to control the state of charge of the batteries. Power flow to or from the traction motor must be controlled to provide the desired acceleration/deceleration and speed of the vehicle. In this process, of controlling the power flow for the battery, traction motor, and generator, all should be managed so that optimal efficiency is achieved. The existing topologies are shown here and will form a base against which the newly proposed topologies of this work can be compared. Below is a summary of the existing topologies which will be discussed in more detail.

- Traditional Input Rectifier/VSI to Output VSI
- Input Rectifier/VSI to Output CSI with Z-Source impedance network
(battery in parallel with Z's capacitor)
- Input Rectifier/CSI to Output VSI with Z-Source impedance network
(battery in parallel with Z's capacitor)
- Input Rectifier/VSI to Output CSI with Z-Source impedance network
(battery in parallel with Input Converter)

Each topology and its operating principles will be briefly reviewed. The traditional Input Rectifier/VSI to Output VSI will be discussed first due to its historical familiarity. This

topology will be used to discuss the general function of the power electronics to deliver and control power.

The hybrid vehicle has the flexibility of choosing where power is to come from and where it is to be delivered to. The goal is to make choices that optimize efficiency. In general, this means that the ICE and generator are to be operated in a narrow range of angular velocity and a relatively small region of torque to supply the average power required. The batteries are to provide the “dynamic” load. That is the power above and below the average power needed. In a vehicle route, the vehicle must accelerate and decelerate many times. The total energy expended by the vehicle on its route divided by the amount of time it takes, gives us the average power. In this example, while the vehicle is accelerating, the traction motors typically require more power than this average power level. This additional momentary power variance is to be provided by the batteries. With this method, the ICE power vs. angular velocity is chosen to be its most efficient operating point. Operation at the most efficient point is not possible with the conventional vehicle and its transmission since the ICE alone must provide all of the range of angular velocity and of power that the vehicle’s wheels/transmission require. Also, the hybrid vehicle is capable of recapturing deceleration energy which is wasted by conventional vehicles. To move power consistent with these goals, several operation modes are encountered. These modes are summarized here since it is desirable for any new topology to be able to achieve each mode.

Hybrid Operational Modes:

1. Battery and Traction Motor mode

The traction motor is lightly loaded, the battery is supplying power to the traction motor, and the generator is off.

2. Battery, Starter Motor and Traction Motor mode

The battery is supplying power to the traction motor and simultaneously providing power to the generator. The generator is momentarily being used as a motor to start the internal combustion engine (ICE).

3. Generator, Battery Discharge and Traction Motor mode

The traction motor is medium to heavily loaded. The generator and the battery are both supplying power.

4. Generator, Battery Charging and Traction Motor mode

During this mode, the Traction Motor load has decreased and the battery transitions from discharging to charging.

5. Regenerative Braking and Battery Charging mode

During this mode, the load at the traction motor becomes negative and the traction motor functions as a regenerative brake (generator). The battery is charging.

Existing Topologies

The first two schematics are of the traditional hybrid bus back to back voltage source

inverter (VSI) topologies and the last three are “Z” source based topologies. Recall that the VSI must have a voltage source that is greater than the desired output voltage level.

$$V_{LL} = \frac{\sqrt{3}}{\sqrt{2}} \frac{V_{dc}}{2} M$$

Where: V_{LL} is the line to line RMS output voltage

V_{dc} is the dc input voltage

M is the modulation index [$0 \leq M \leq 1.0$]

Therefore, the VSI is considered a buck converter. If V_{dc} cannot be as high as is needed, then it would be necessary for a DC/DC converter to be added to the circuit architecture to achieve the required input voltage. This is one of the limitations of the VSI topologies that are overcome with the family of Z-Source topologies.

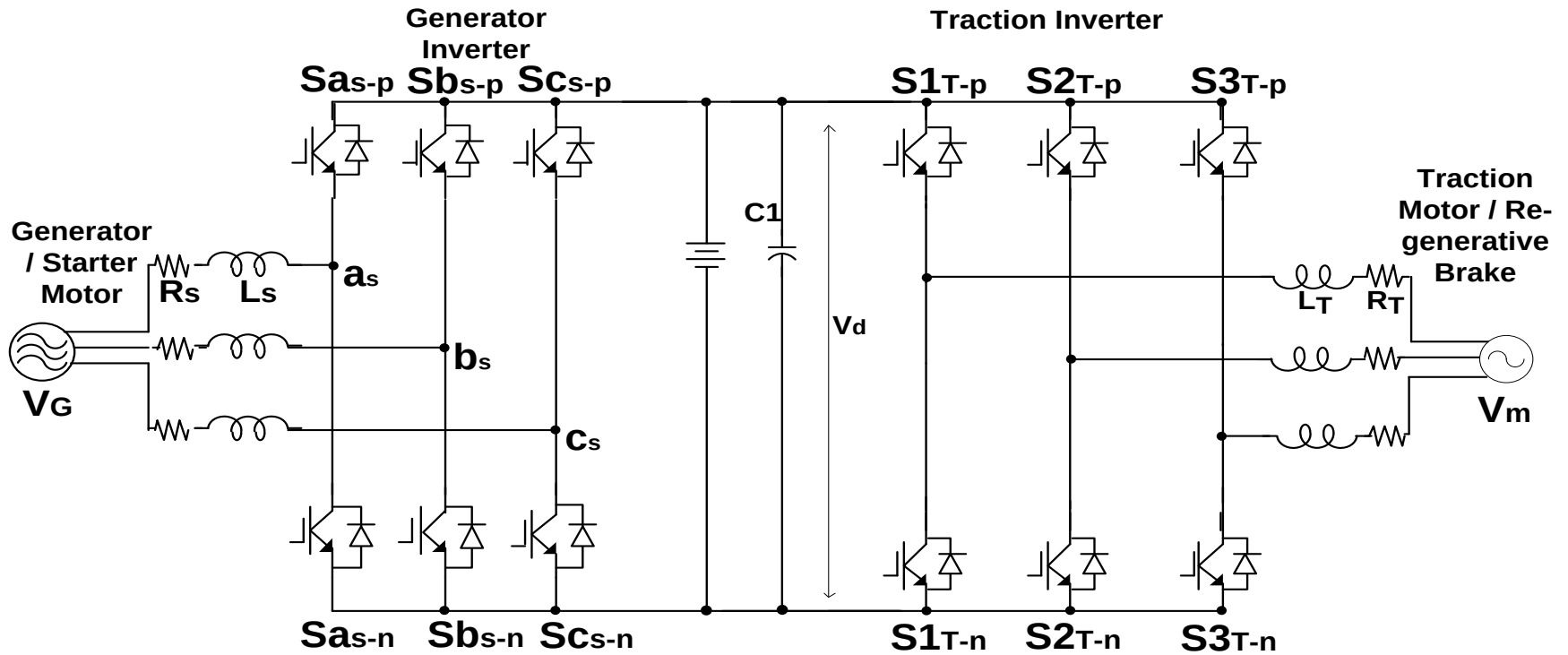


Figure 8 Traditional Input Rectifier/VSI to Output VSI.

The left end of the schematic shows the generator which is connected to the ICE. This end is considered the power flow input. The term rectifier is also used since the input converter may be used as a passive rectifier. Voltage sources in the center and a VSI at the output

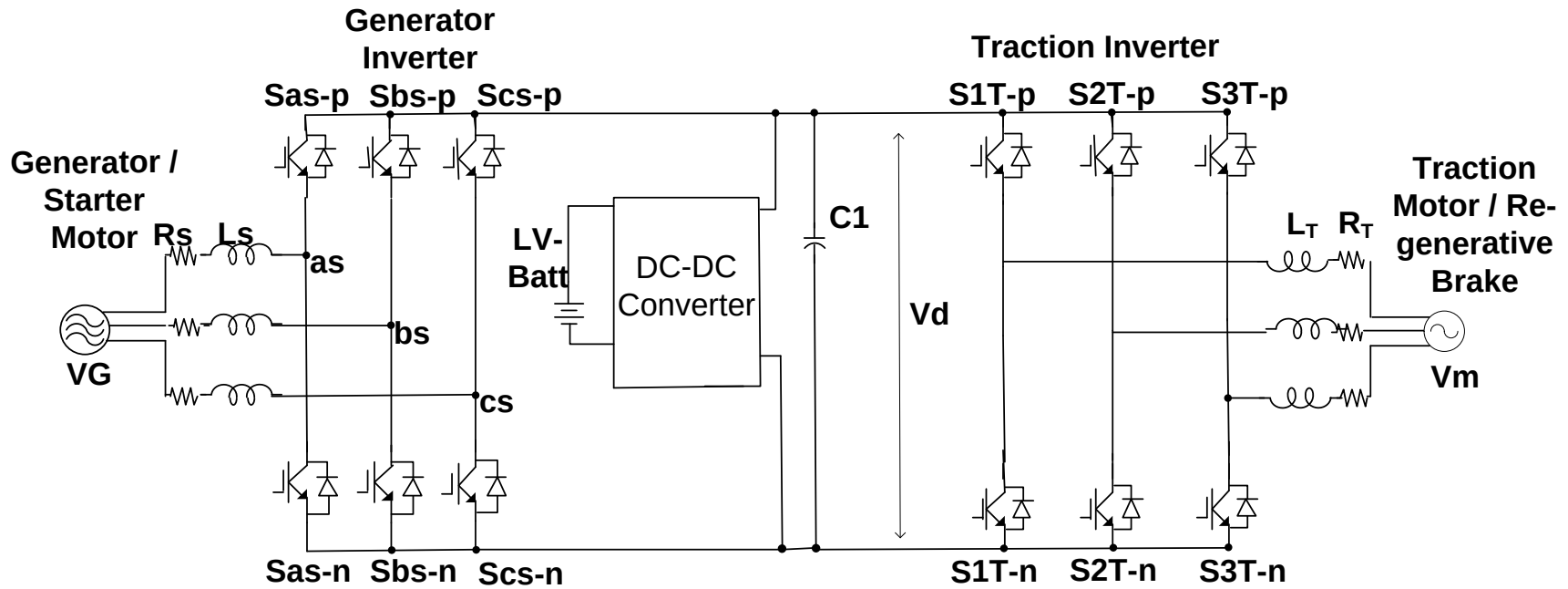


Figure 9 Traditional Input Rectifier/VSI to Output VSI with DC/DC Converter.

The left end of the schematic shows the generator which is connected to the ICE. This end is considered the power flow input. The term rectifier is also used since the input converter may be used as a passive rectifier. Battery and DC/DC converter in the center and a VSI at the output

The next circuit architecture is the Input Rectifier/VSI to Output CSI with Z-Source impedance network and the battery is in parallel with Z 's capacitor. Because of the bidirectional current flow allowed by the input converter (on the left of the schematic), the input converter is called a VSI. Notice that the output converter (right side) only allows one directional current flow but bidirectional voltage blocking. As such, it is called a CSI. The network in the center is made up of the unique combination of capacitors and inductors and is called the Z-Source (Impedance-Source).

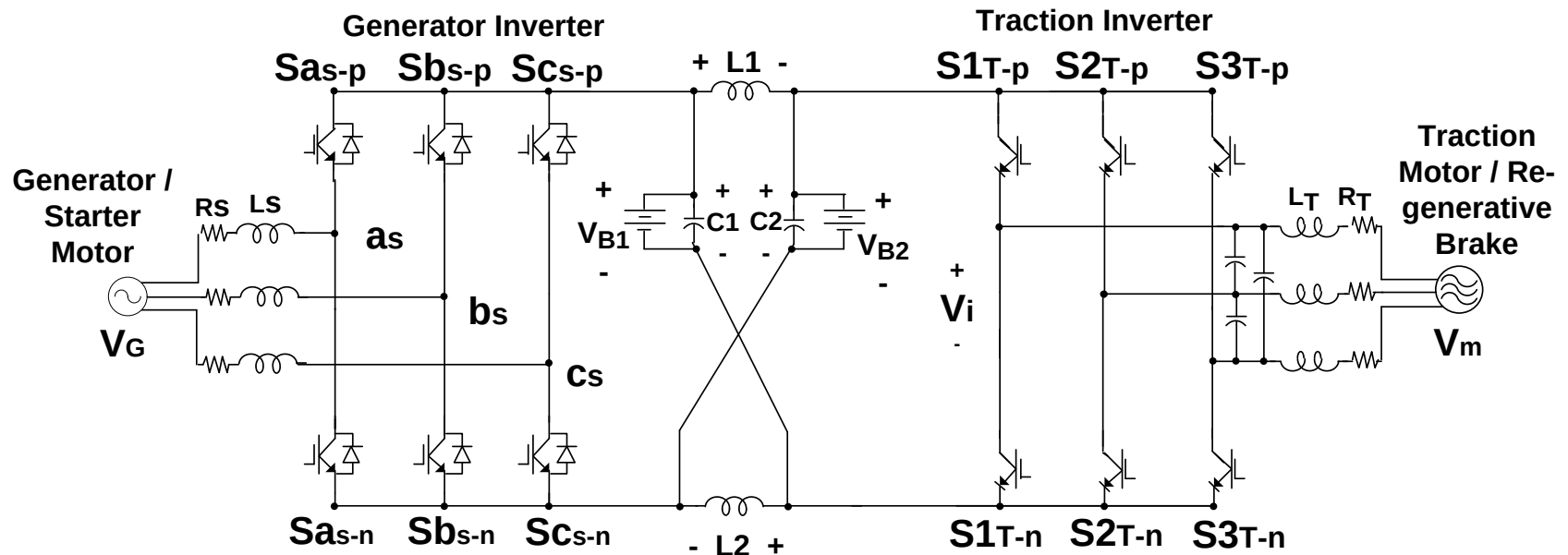


Figure 10 Input Rectifier/VSI to Output CSI with Z-Source impedance

Network and battery in parallel with Z's capacitor.

The left end of the schematic shows the generator which is connected to the ICE. This end is considered the power flow input. The term rectifier is also used since the input converter may be used as a passive rectifier. Z-Source network in the center and a CSI at the output

The third circuit architecture is the Input Rectifier/CSI to Output VSI with Z-Source impedance network and the battery is in parallel with Z 's capacitor. This topology is the same as directly above except that the converters are swapped end for end. In this case, the input converter is the CSI which allows only one directional current flow and bi-directional voltage blocking while the output converter is the VSI converter. Its schematic is now shown below.

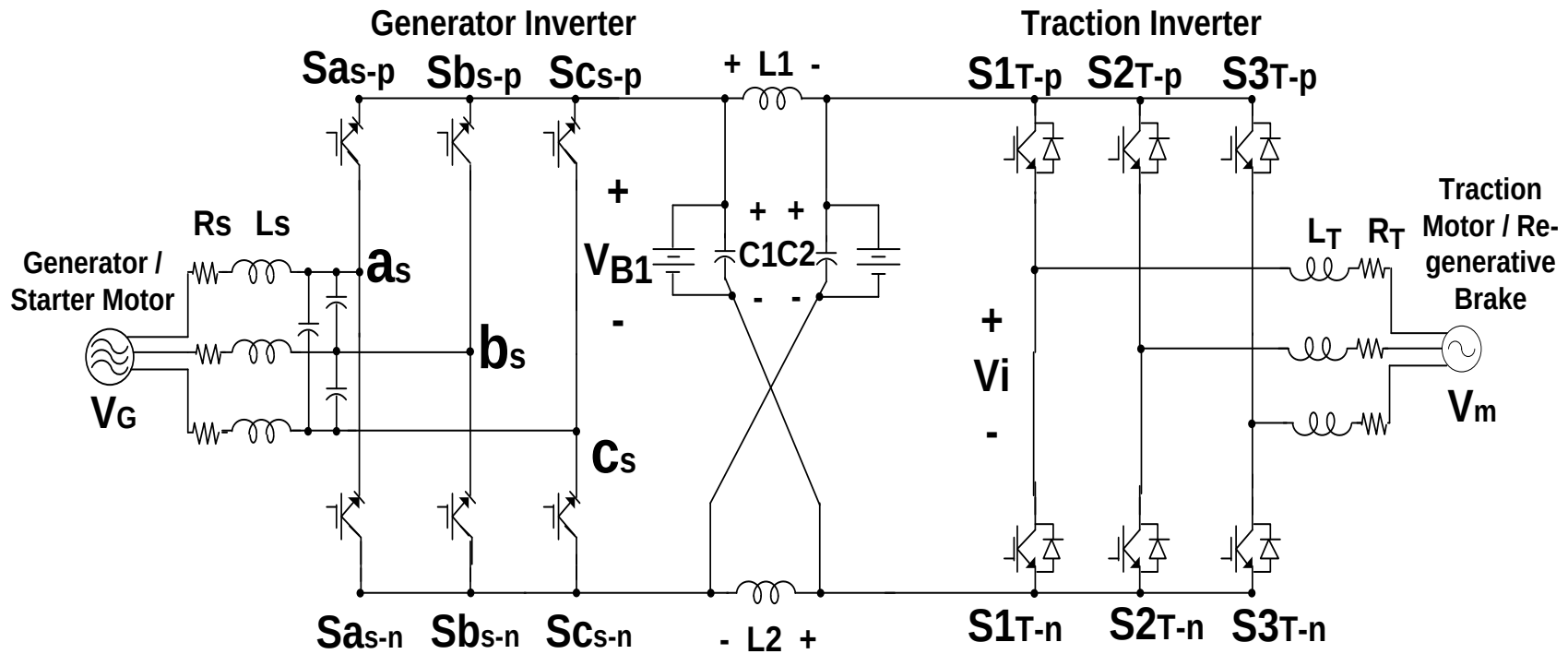


Figure 11 Input Rectifier/CSI to Output VSI with Z-Source impedance

Network and battery in parallel with Z's capacitor.

The left end of the schematic shows the generator which is connected to the ICE. This end is considered the power flow input. The term rectifier is also used since the input converter may be used as a passive rectifier. Z-Source network in the center and a VSI at the output

The fourth circuit architecture is the Input Rectifier/VSI to Output CSI with Z-Source impedance network and the battery is in parallel with the Input Converter. This is like the second Z-Source circuit shown above except that the battery position is different. The schematic is shown below.

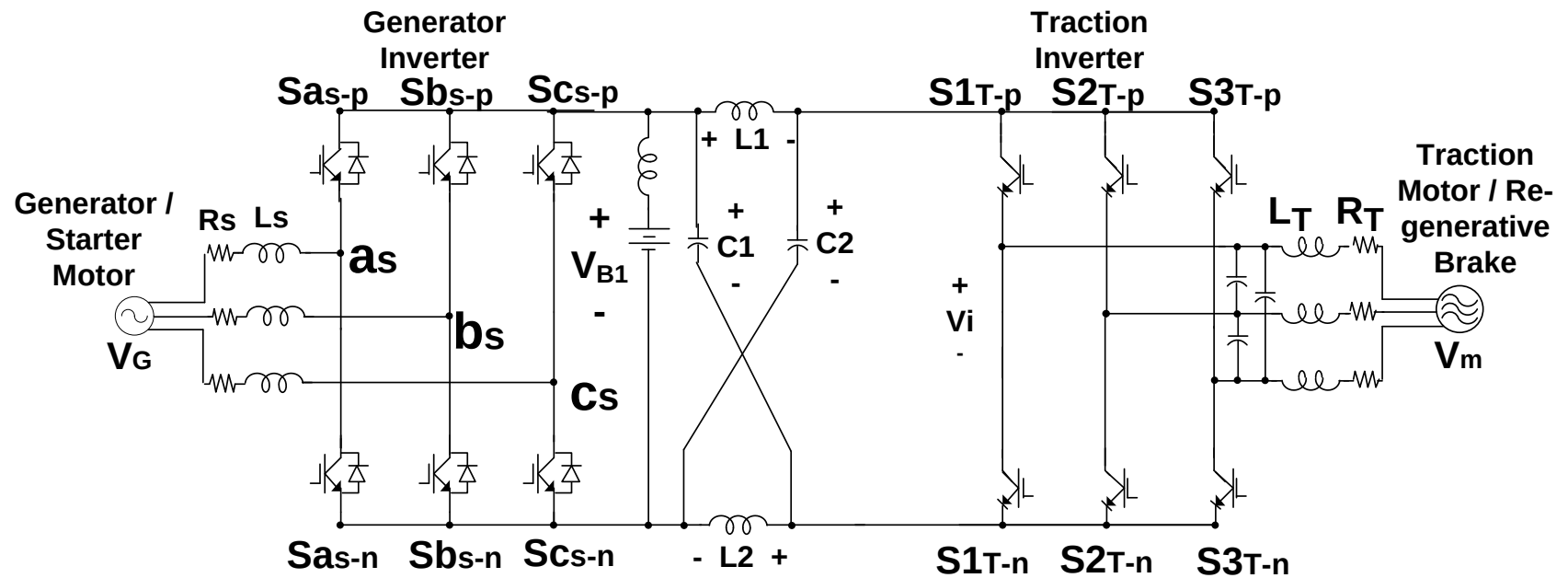


Figure 12 Input Rectifier/VSI to Output CSI with Z-Source impedance

Network and battery in parallel with Input Converter.

The left end of the schematic shows the generator which is connected to the ICE. This end is considered the power flow input. The term rectifier is also used since the input converter may be used as a passive rectifier. Z-Source network in the center and a CSI at the output

3. EVALUATION OF MAJOR HEV COMPONENTS AND OVERALL OPERATION OF HEV

One of the most effective features of the hybrid vehicle is its ability to decouple the angular velocity of the ICE from the velocity of the vehicle. The extent of which a particular hybrid is able to do this allows the ICE operating point to be kept within its most efficient operating points. . It is the hybrid equipment (generator, inverters, battery and converter, and traction motors) that allow the decoupling of ICE torque and speed from that of the traction wheels. This equipment also allows the recapture of braking energy which would be lost with non-hybrid vehicles.

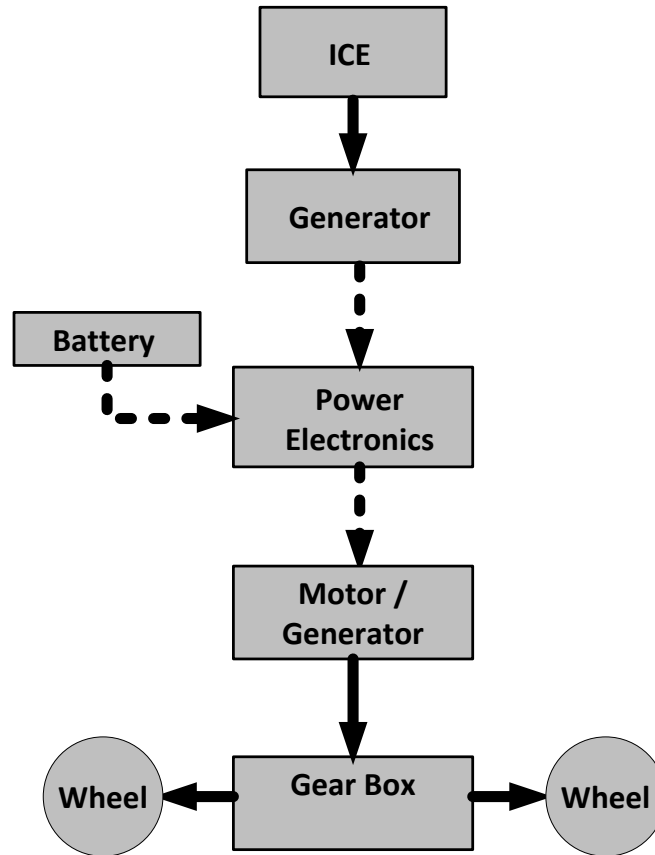


Figure 13 Series Hybrid Electric configuration

The traditional vehicle has a transmission that allows a decoupling of ICE torque speed from vehicle speed to some degree. Due to the transmissions several discrete gear ratios, the ICE can operate at one torque and speed point and the vehicle wheels can operate at a different torque-speed point; however, the torque speed decoupling is not complete with the traditional transmission. A specific torque speed point can also be referred to as a specific power point. In general, the power point of the ICE is equal to the power point of the vehicle wheels (neglecting losses). A particular power point can be achieved with an infinite number of torque-speed combinations most of which occur at low efficiency and just a small grouping of such points is at high efficiency. It is then desirable to completely decouple the ICE torque-speed operating point from that of the vehicle

wheels so that the ICE can remain operating in its most efficient region. The hybrids are able to achieve this decoupling to a greater extent than the traditional transmission and each different hybrid type (mild hybrid, full hybrid) is able to improve this decoupling to lesser or greater degrees. The series and series/parallel full hybrids are capable of completely decoupling the torque-speed operating point of the ICE from that of the vehicle wheels and the ICE power and vehicle wheel power is also decoupled to the extent that the battery can source or sink the power difference. If power from the ICE is different than power to or from the traction motors, this difference of power can be provided by or absorbed by the battery. Also, it is the battery that also allows braking energy to be stored. The main components that will be discussed in this section are the ICE, generator, battery, inverters (controller in the figure above), and traction motors. Each of these components has its own set of characteristics and it is desirable to operate them in an efficient manner. In the following sections, each of these major components is discussed and analyzed to determine what constraints they impose on the overall design of the hybrid topology and how these constraints can be managed in a more efficient manner. First, we consider the ICE of the hybrid vehicle.

3.1 Characteristics of the Internal Combustion Engine (ICE)

Below is a torque vs. angular velocity graph of a typical diesel ICE. Laid on top of this graph are the efficiency maps of the ICE. The inner most loop (from 1212 to 1575 revolutions per minute and 900 to 1650 Newton Meters of Torque) is the operating region of highest efficiency. Operating points outside of this region are of lesser efficiency and

one can see that efficiency begins to decrease rather quickly for operating points further outside of this region.

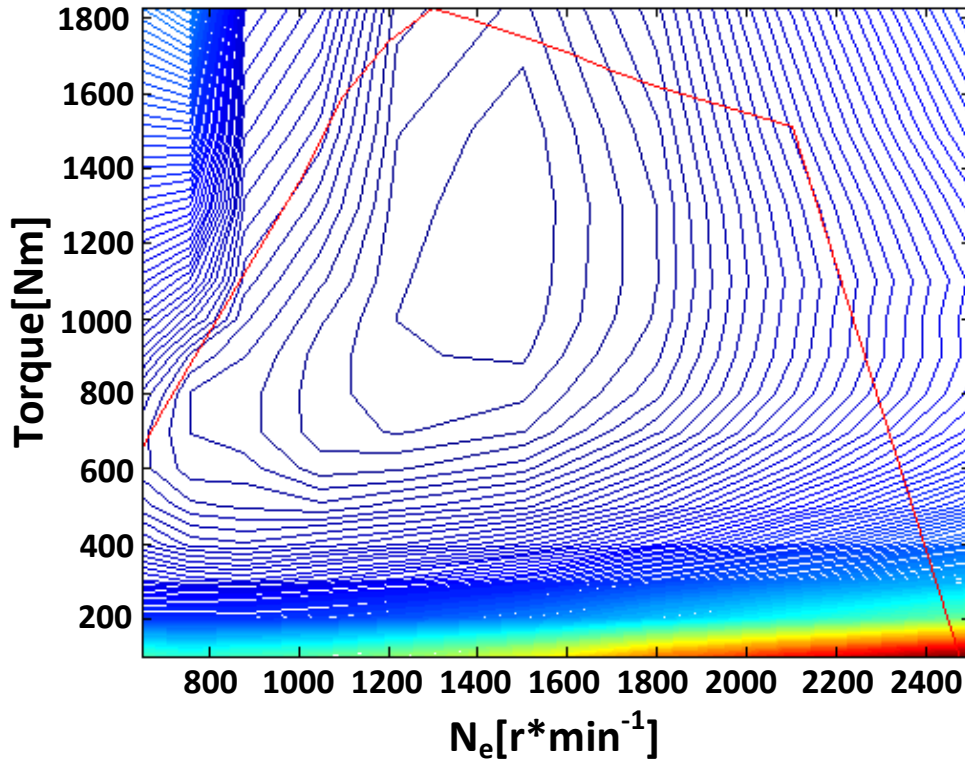


Figure 14 Typical Torque Vs. Speed curves of a diesel ICE.

Highest efficiency operation is shown in the center most enclosed line spanning the region from 1212 to 1575 revolutions per minute and 900 to 1650 Newton Meters of Torque.

For a diesel engine, this region may achieve efficiency as high as 42% with a target efficiency of 50% by the year 2015[28]. Since the efficiency of the ICE is sensitive to its torque – speed operation point, a significant amount of savings can be achieved by ensuring that the ICE operating point does not deviate from this region. Since the generator is connected to the ICE, it should be designed to operate at the ICE's optimum

speed and to produce the desired voltage at that speed. Next the hybrid battery is discussed.

3.2 Characteristics of the Hybrid Battery Pack

The hybrid vehicle uses several power electronics components. Such components are an AC to DC inverter connected to the generator, an AC to DC inverter connected to the traction motors and a DC/DC converter connected to the battery and to the inverters. See the following schematic.

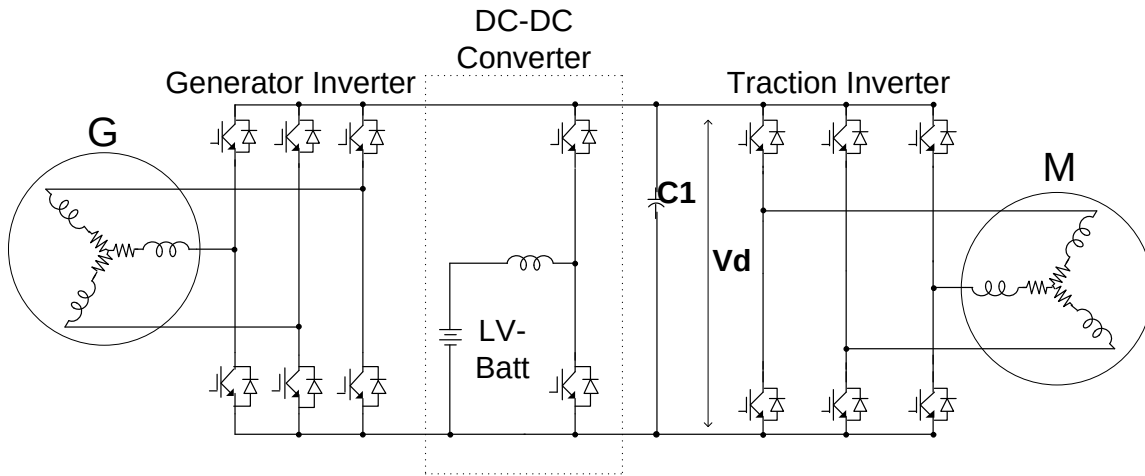


Figure 15 Traditional Back to Back VSI / VSI hybrid topology

The AC to DC inverters and DC/DC converter are connected together through a common set of conductors called the DC-Link. It is typical that the battery voltage is different from that of the DC-Link for several reasons. As such, the battery requires a DC/DC converter to control the difference in voltage levels between that of the battery and of the

DC-Link. Below is a discussion about the batteries and issues related to adding more battery cells in series and in parallel.

3.2.1 Comparison of the high voltage battery vs. the low voltage battery. High voltage battery option.

The high voltage battery has the advantage of being able to connect directly to the DC-Link without the use of a DC-DC converter. This assumes that the DC-Link is held at a constant voltage level and not all hybrids operate in that manner. The high voltage battery option is simple in design and uses fewer electronic components. It does, however, require a greater number of battery cells to be stacked in series. There is also a fundamental problem with connecting batteries in series. If the Lithium Ion battery is used as an example, due to its lighter weight and relatively fast charging rate, e.g. Valence Technologies U27-FN130, it can receive a maximum charge current of 100A. A series connection of 55 batteries is needed to achieve a total voltage of 700 volts. With such a series connection, a failure of any one of the 55 batteries will cause a serious degradation of performance. The reliability equation for series-parallel arrays of electronic components is as follows.

$$R(t) = [1 - p^n F(t)^n]^m - [1 - (1 - qF(t)^n)]^m \quad (\text{eq 3.1})$$

Where:

- R(t) is the reliability,

- p is the conditional probability of a short,
- q is the conditional probability of an open,
- m is the number of parallel paths,
- n is the number of components in series,
- $F(t)$ is the cumulative distribution function of time to failure of series components [19]

In this particular case, the short circuit failure rate is quite low for batteries. Typically, battery failures occur from an increase in resistance and or a decrease in voltage. As a result, reliability decrease is much more likely to occur from series connections than from parallel connections.

If it is necessary to receive a charge at greater than 100 A, additional parallel combinations of 55 series batteries will be needed. As can be seen, the number of batteries required can add up quickly. Also, with series connections, each battery is slightly different than the other batteries that it is connected to (different internal resistance, different voltage level, etc.) As a result, some of the series batteries are putting out more power than others. Under high current levels, a poorly functioning battery may actually be dissipating more power than it is providing. See Figure 16. The net result is a compromised performance of the whole stack.

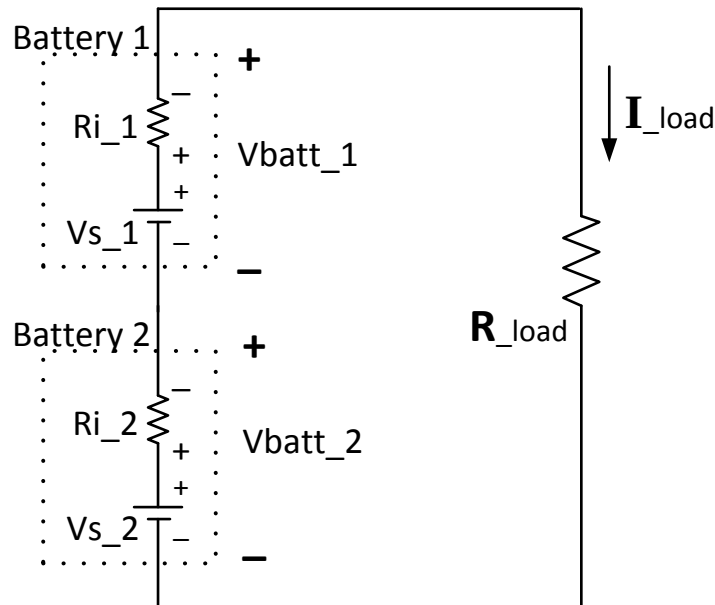


Figure 16 Series Combination of Battery Cells

If I_{load} is large and V_{s_1} is small, V_{batt_1} can be negative and Battery 1 can be absorbing power from Battery 2.

Where R_i is the internal resistance of a battery, V_s is the internal voltage potential of a battery, V_{batt} represents one battery unit

As the age of the batteries increase, these conditions worsen. Due to these factors, the high voltage battery has a lower reliability than the DC-DC boost converter and low voltage battery combination. Battery management electronics can be added to monitor individual battery condition and allow for by-passing weak cells, but this adds to the complication and cost.

Typically, a high voltage series stack is more costly than a low voltage stack of the same Amp hour rating. Also with the high voltage battery stack comes the additional safety concerns for service personnel, rescue workers, etc.

3.2.2 Comparison of the high voltage battery vs. the low voltage battery. Low voltage battery with DC/DC converter option.

With a low voltage stack, a DC-DC boost converter is required. Since the low voltage stack voltage level is less than that of the DC Link, a boost converter is required between the DC Link and the batteries. The disadvantage of this low voltage arrangement is that this additional circuit (DC-DC boost converter) is needed. Along with the additional circuitry come additional cost, complexity, and lowering of reliability, due to the additional components. The advantages of this design however, is that the total number of batteries in series will decrease, and this will increase system reliability for the reasons discussed above.

The use of a DC-DC converter adds an extra level of control for the battery SOC by controlling the DC output voltage level. Although this level of control is not needed to control battery SOC since coordinated control of the generator inverter/rectifier and traction motor inverter/rectifier also achieve SOC control. Still, the DC-DC converter can provide this as well as an added level of battery health monitoring and control. The low voltage option also reduces voltage levels present when the vehicle is not running which can reduce risk factors to passengers and emergency personnel in the case of a collision involving the vehicle.

3.2.3 Summary of High Voltage Battery Option vs. Low Voltage Battery Option

High Voltage Option

Pros:

- Battery Voltage = DC Link Voltage and a DC-DC converter is not Required

Cons:

- Greater number of Batteries in series and a related decrease in reliability of the battery stack

Low Voltage Option

Pros:

- Lower number of batteries in series and a related increase in reliability of the battery stack.
- Extra level of control for battery SOC
- Reduced non-operating voltage levels
- Reduced energy loss during low power operation
- Reduced THD during low power operation
- Reduced total number of cells

Cons:

- A DC-DC converter is required
- Decreased reliability due to additional components.

For these reasons, a lower voltage battery stack is usually preferred.

3.3 Characteristics of Inverters and Converters

Perhaps the most significant component of the inverters and converters is the switching device. For inverters and converters of this power rating, this device is the IGBT module.

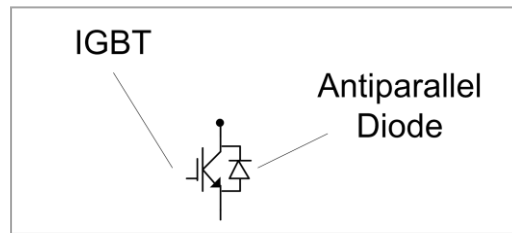


Figure 17 IGBT module used in inverters and converters

The IGBT module consists of an insulated gate bipolar junction transistor and a PN junction diode. The losses of these devices are of concern to this power loss analysis. For example, the following equations show the switching losses and conduction losses of an inverter's IGBT and diode. In these equations, notice that each of the switching losses (P_{on} , P_{off} , and P_{rr}) are proportional to V_{cc} which is the DC-Link voltage. The IGBT conduction losses P_i and diode conduction losses P_d are not related to the DC-Link voltage.

$$P_{on} = \frac{1}{8} V_{cc} \cdot t_{rN} \frac{I_{cM}^2}{I_{cN}} F_s \quad (\text{eq 3.2})$$

$$P_{off} = V_{cc} \cdot I_{cM}^2 \cdot t_{fN} \cdot F_s \left(\frac{1}{8 \cdot I_{cN}} \right) \quad (\text{eq 3.3})$$

$$P_{rr} = F_s V_{cc} \left[\left(0.1404 + \frac{0.1902}{\pi} \frac{I_{cM}}{I_{cN}} + 0.0075 \left(\frac{I_{cM}}{I_{cN}} \right)^2 \right) Q_{rrn} \right. \\ \left. + \left(0.05 \frac{I_{cM}}{I_{cN}} + \frac{0.8}{\pi} \right) I_{cM} \cdot t_{rrN} \right] \quad (\text{eq 3.4})$$

$$P_i = \left(\frac{1}{8} + \frac{M}{3\pi} \cos(\theta) \right) \frac{V_{ceN} - V_{co}}{I_{cN}} I_{cM}^2 + \left(\frac{1}{2\pi} + \frac{M}{8} \cos(\theta) \right) V_{co} I_{cM} \quad (\text{eq 3.5})$$

$$P_d = \left(\frac{1}{8} - \frac{M}{3\pi} \cos(\theta) \right) \frac{V_{FN} - V_{Fo}}{I_{cN}} I_{cM}^2 + \left(\frac{1}{2\pi} - \frac{M}{8} \cos(\theta) \right) V_{Fo} I_{cM} \quad (\text{eq 3.6})$$

[25]

Where:

P_d = diode conduction loss

P_i = IGBT conduction loss

P_{off} = Turn off loss of the IGBT

P_{on} = Turn on loss of the IGBT

P_{rr} = reverse recovery loss of the diode

F_s = switching frequency

I_{cM} = maximum collector current

I_{cN} = rated collector current
 M = modulation index
 Q_{rrn} = rated recovery charge
 t_{fN} = rated fall time
 t_{rN} = rated rise time
 t_{rrN} = rated recovery time
 V_{cc} = DC bus voltage
 V_{ceN} = rated collector to emitter voltage
 V_{co} = threshold collector emitter voltage
 V_{FN} = rated diode forward voltage
 V_{Fo} = threshold diode forward voltage

The significance of these equations will become more apparent later in this discussion.

Next, the traction motors will be discussed.

3.4 Traction Motor Operating Conditions

Below in Figure 18, are images that represent the operating speed of city (urban) driving. These figures are prepared by the United States Environmental Protection Agency (EPA) and are based upon their studies of typical vehicle operating conditions. This EPA chart shows the Urban Dynamometer Drive Schedule.

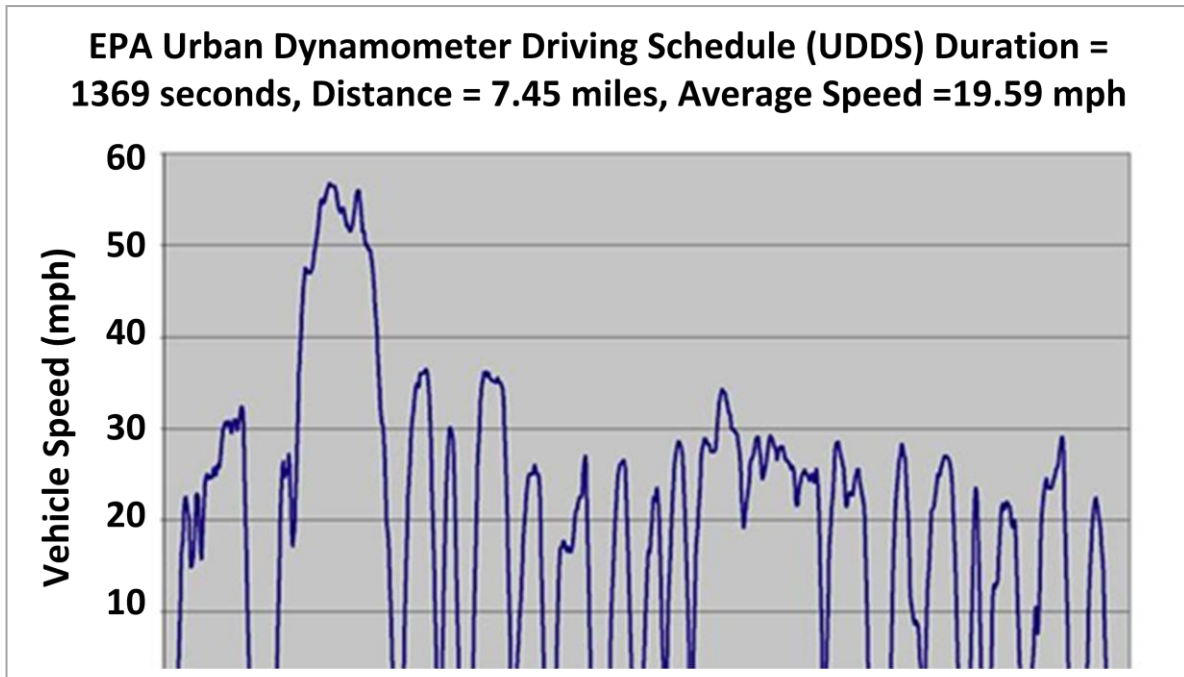


Figure 18 EPA Urban Dynamometer Driving Schedule (UDDS)

This chart shows that the operating velocities of urban driving are far below full speed, for the vast majority of time. Since the city or commuter bus operates with driving patterns similar to those of the EPA UDDS, this chart is relevant to this analysis.

The traction motors are coupled to the traction wheels through a constant ratio gear box and therefore, the traction motor angular velocity is directly related to the vehicle velocity. Therefore, the traction motor angular velocity required is much below full

speed for the vast majority of time and the line to line voltage required by the motor to achieve the desired current is much lower than full voltage for the vast majority of time.

3.5 Summary of Hybrid Major Components

The major components of the hybrid vehicle have been reviewed and the relevant operating conditions and characteristics of each component have been considered. Considering the traditional hybrid topology, shown here again for convenience, the component characteristics will be summarized from left to right.

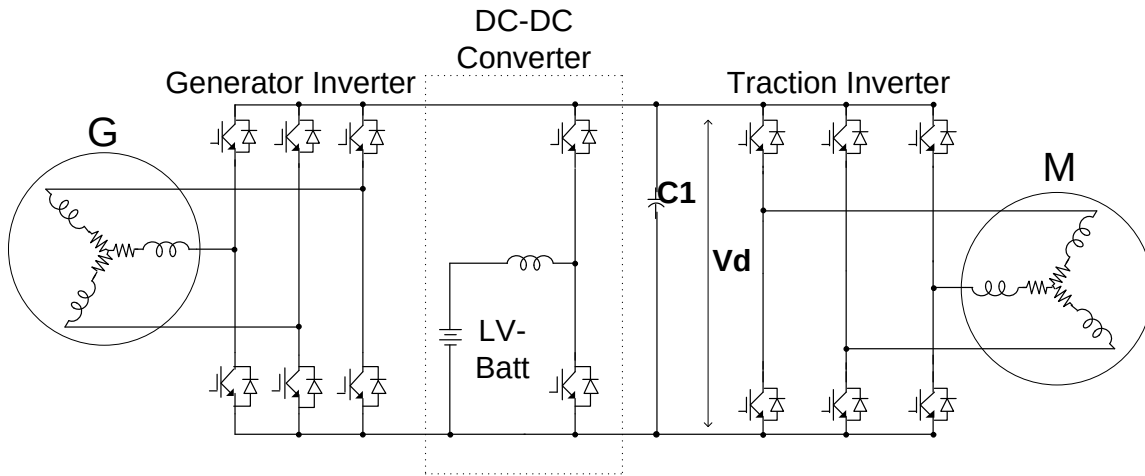


Figure 19 Traditional Back to Back VSI / VSI hybrid topology

Starting with the ICE, not shown above, it was determined that a constant operating speed would be the most efficient for the ICE. As a result of this, the generator will then be operated at a constant speed and therefore a constant voltage. In general, generators can be designed to be more efficient if they generate at high voltage and low current. The greatest gains in efficiency can be achieved by catering to the ICE's efficiency sensitivity

to torque and speed operating points. Therefore, the generator will output a constant high voltage. This in turn sets the DC-Link voltage to be high.

The battery voltage desired is significantly below the voltage level of the DC-Link as previously discussed, and the voltage output of the traction inverters will much below full voltage for the vast majority of vehicle operating points since the vehicle operating speeds were shown to be well below full speed for this amount of time.

Traction motor line to line voltage can be lowered by lowering the modulation index (or decreasing vector magnitude when using vector control); however, we also saw that the switching losses of the inverter switching devices (IGBT and freewheeling diode) were directly proportional to the DC-Link voltage. With this in mind, it is desirable to keep the voltage across the switching devices of the traction inverter (TI) and DC/DC converter as low as possible. This could be done by outputting a low voltage from the generator and then increasing the generator voltage as need by the traction motor. Raising this voltage can be achieved in two ways. The first if to initially operate the ICE at a low speed and then increase this speed as necessary, but as discussed previously, this in not desirable based upon the ICE's efficiency map. Another method is to generate at low voltage and constant speed and then boost the voltage by lowering the GI modulation index. This method would cause generating to be done at low voltage for the majority of time and therefore at higher current than necessary which is generally not efficient. Also,

this uses the generator's inductance to perform the boost function and this also raises the losses encountered by the generator.

In summary, it is desired that the generation be held at a constant high voltage, that the battery voltage remain low, and that the voltage across the TI be variable and controlled to be as low as possible for the present velocity of the bus. This is not possible with the traditional topology. The DC-Link of the traditional topology (see Figure 19) is common to both the GI and TI and thereby imposes that the voltage across the GI is at all times equal to the voltage across the TI. Hence, a new topology is needed to achieve the more favorable operational conditions.

4. PRESENTATION AND BRIEF ANALYSIS OF PROPOSED TOPOLOGIES

Being able to operate the generator inverter's DC-Link voltage at a high voltage and the traction inverter's DC-Link voltage at a low voltage provides very significant gains in efficiency. Further, it should be pointed out that the traction inverter must handle the total vehicle power (generator and battery power) which causes an increase in efficiencies of the traction inverter to be even more significant.

What is desired is a topology that can allow the ICE to operate in its most efficient torque and speed region, a generator designed to operate at high voltage and low current at this speed, and a DC-Link that can offer as low of a DC voltage to the traction invert as is dictated by constant volts/Hz operation of the traction motors.

Ideally, the new topologies with lower TI losses, would not incur any additional losses in the process of decoupling the GI voltage from the TI voltage. However, the process of providing lower voltage to the TI does incur additional conversion losses. The trick is to incur less additional conversion losses than is saved by the reduced losses in the TI. That is, even though the process of decoupling the GI DC-Link voltage from the TI DC-Link voltage causes some additional conversion losses, the goal is to achieve a greater reduction of losses in the TI which will more than compensate for this and yield a net reduction in losses.

The following sections 4.1 through 4.8 describe the proposed new topologies. Chapter 5

will show the power losses of these new topologies as compared to the traditional topology.

4.1 VSI / VSI with Conventional Mid-Link DC / DC Converter

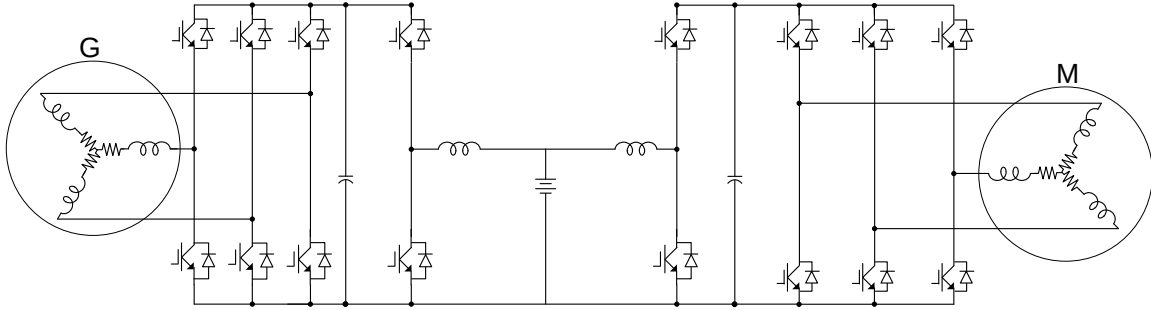


Figure 20 VSI / VSI with Conventional Mid-Link DC / DC Converter

The topology shown in Figure 20 has as its basic structure a generator VSI and traction motor VSI. The Low voltage battery is coupled to the DC-Link through two DC/DC converters which boost from the battery toward the GI and toward the TI and buck from the GI toward the battery and from the TI toward the battery. This topology offers a Generator inverter DC voltage that is independent from the DC voltage at the traction inverter. The TI DC-Link voltage can be as high as $V_{BATT} \frac{1}{1-D}$ and as low as V_{BATT} .

Only the generator power flows through the generator inverter and through the left DC/DC converter whereas both the generator power and the battery power flows through the right DC/DC converter and the TI. With this topology, the generator can be designed for high voltage and low current. The battery can be a low voltage battery stack due to the GI's DC/DC converter. The traction inverter's DC-Link voltage (V_{DC_TI}) can range

from the battery voltage (V_{BATT}) to the V_{DC_TI} required for maximum vehicle speed. V_{DC_GI} and V_{DC_TI} are independent of each other and only dependent on V_{BATT} . The topology allows the more efficient high voltage low current generator design and the more efficient low V_{DC_TI} across the switching devices of the TI for operation at less than maximum vehicle speed. The following diagram summarizes the per unit power that must flow through each section. Where possible, the goal is to implement the least efficient converters where the power flow is lowest and to implement the most efficient conversion processes where power flow is greatest. In this case, however, the DC/DC conversion on the GI side (with $\frac{1}{2}$ per unit power flow) is just as efficient as that on the TI side (with 1.0 per unit power flow).

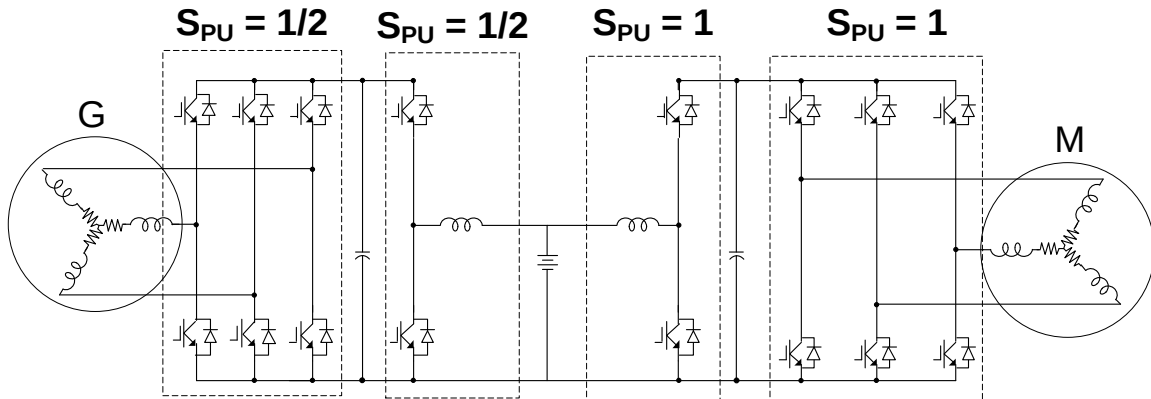


Figure 21 VSI / VSI with Conventional Mid-Link DC / DC Converter.

Per unit power flow through each inversion or conversion process is indicated.

State of charge (SOC) of the batteries can be controlled by controlling the relative power flow from the generator, to or from the traction motors, and or controlling the switching duty cycles of the DC / DC converters.

4.2 VSI / VSI with “H” Bridge Coupled Battery Pack

The topology shown in Figure 22 is based upon the well-known VSI /VSI configuration where a VSI is used at both the generator end and traction motor end of the topology. In this particular case, the battery pack can be connected to the DC-Link in two ways, or not at all.

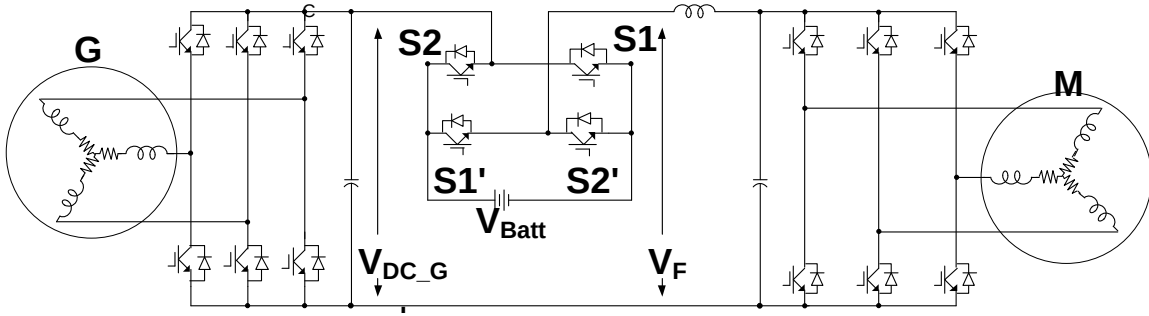


Figure 22 VSI to VSI topology with an “H” bridge coupling the battery pack to the DC-Link

If switches S1 and S1' are gated on simultaneously, the voltage across the LC filter at the TI is:

$$V_F = V_{DC_GI} - V_{BATT} \quad (\text{eq 4.1})$$

If S2 and S2' are gated on simultaneously:

$$V_F = V_{DC_GI} + V_{BATT} \quad (\text{eq 4.2})$$

If S1 and S2' are gated on simultaneously or S1' and S2:

$$V_F = V_{DC_GI} \quad (\text{eq 4.3})$$

Because of the inductor of the LC filter at the TI end, the voltage across the TI can be controlled to be any voltage level between (eq 4.1) and (eq 4.2).

The following figure shows the per unit power that must be managed by each inverter and converter.

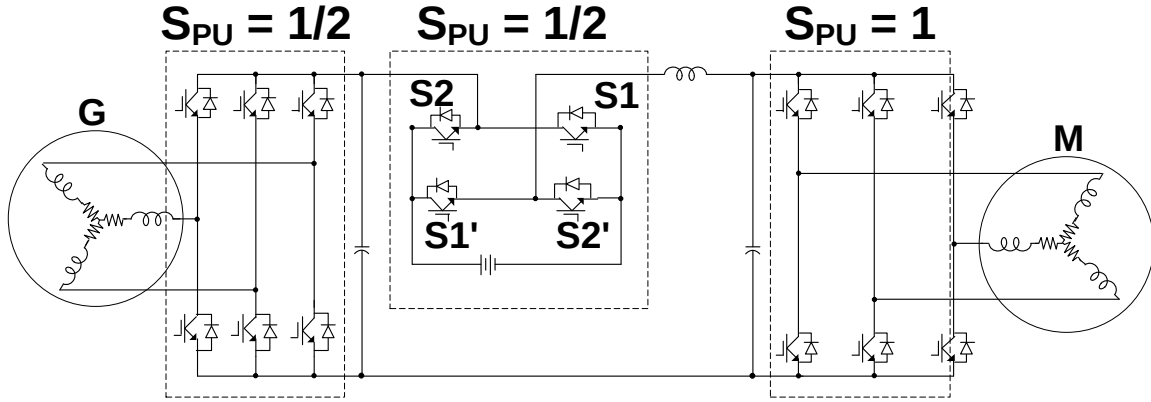


Figure 23 VSI to VSI topology with an “H” bridge coupling the battery pack to the DC-Link.

Per unit power flow through each inversion or conversion process is indicated.

Notice that while S1 and S1' are gated on, that the battery is being discharged. While S2 and S2' are gated on the battery is being charged and in the third and fourth states, the batteries are neither charged nor discharged. As a result, the state of charge (SOC) of the battery pack can be controlled. However, the SOC of the battery and the voltage across the TI cannot be effectively controlled at the same time which invalidates this topology.

A second issue with this new topology is that regenerative braking will not work at low speeds when $V_{DC_TI} < V_{BATT}$.

4.3 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter

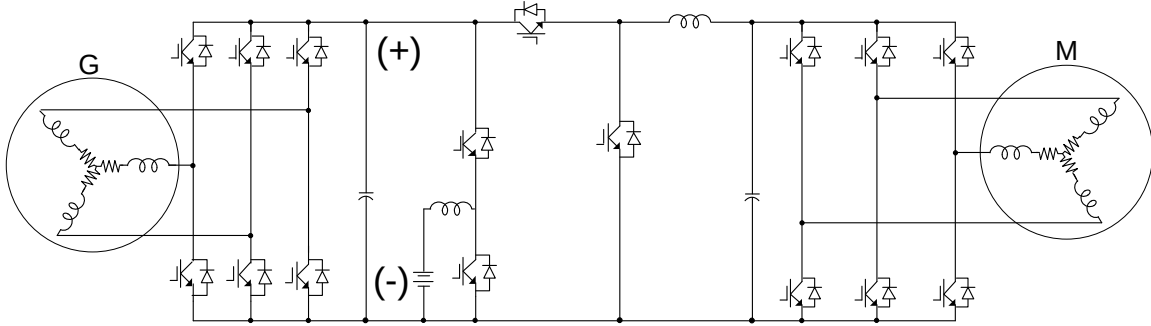


Figure 24 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter

The topology shown in Figure 24 uses the standard VSI / VSI platform. Added to this topology are a boost converter for the battery pack and a buck converter between the battery converter and the TI. This configuration allows the DC-Link voltage at the GI to be held constant and allows the DC-Link voltage at the TI to be varied from zero to the voltage level required for maximum traction motor speed.

$$V_{DC_TI} = V_{DC_GI} * D \quad (\text{eq 4.4})$$

Hence the traction motors can be operated via constant volts/Hz control while holding the TI modulation index at 1.0. Holding the voltage across the TI to the lowest level needed to support the required output voltage to the motors greatly reduces the TI switching losses. Holding the modulation index of the TI at 1.0 reduces the harmonic content of the inverter output and thereby reduces losses in the traction motors as well.

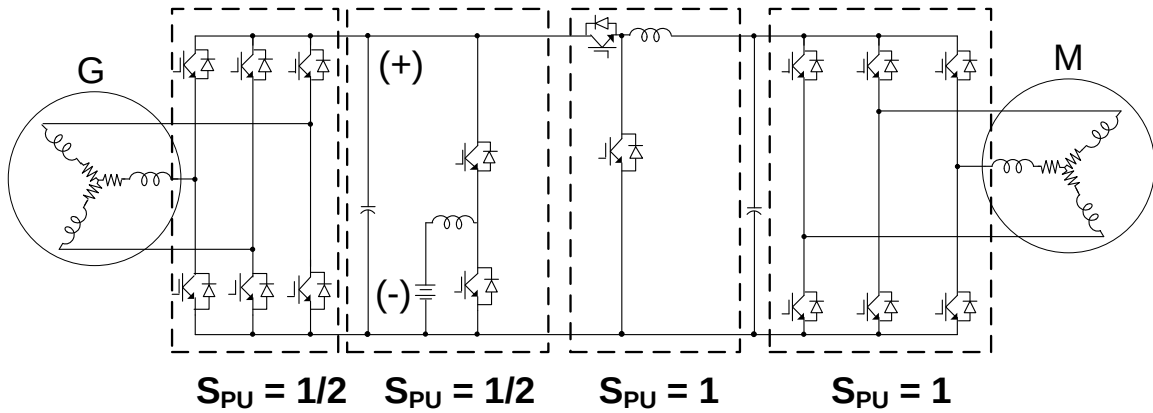


Figure 25 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter.

Per unit power flow through each inversion or conversion process is indicated.

The kVA rating of the battery's boost converter only needs to be rated for the battery power; however, the kVA rating of the TI's buck converter must be rated for total system power.

4.4 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter

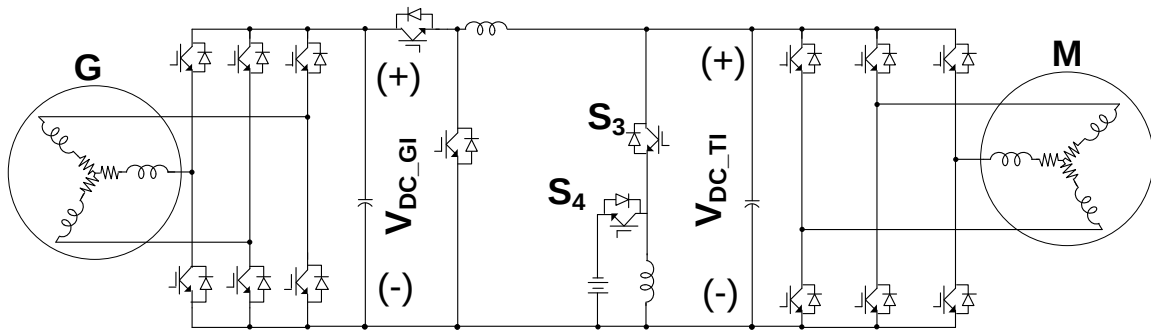


Figure 26 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter

The configuration shown in Figure 26 uses the traditional back to back VSI / VSI topology. Added to this topology is a buck converter on the GI side that bucks voltage from the GI toward the TI and boosts voltage from the TI toward the GI. This converter can buck from the GI voltage V_{DC_GI} all of the way to zero volts. The low voltage battery is connected to the DC Link on the TI side via a buck-boost converter that is capable of bucking voltage all the way down to zero volts and boosting voltage up to infinity (theoretically).

$$V_{DC_TI} = V_{BATT} \left(\frac{D}{(1-D)} \right) \quad (\text{eq 4.5}).$$

This configuration allows the complete decoupling of voltage levels from the GI end of the DC-Link to the TI end. The DC-Link voltage level at the TI can be varied from 0V to as high as is needed for constant voltz/Hertz operation, while at the same time, the DC-Link voltage at the GI can be held constant.

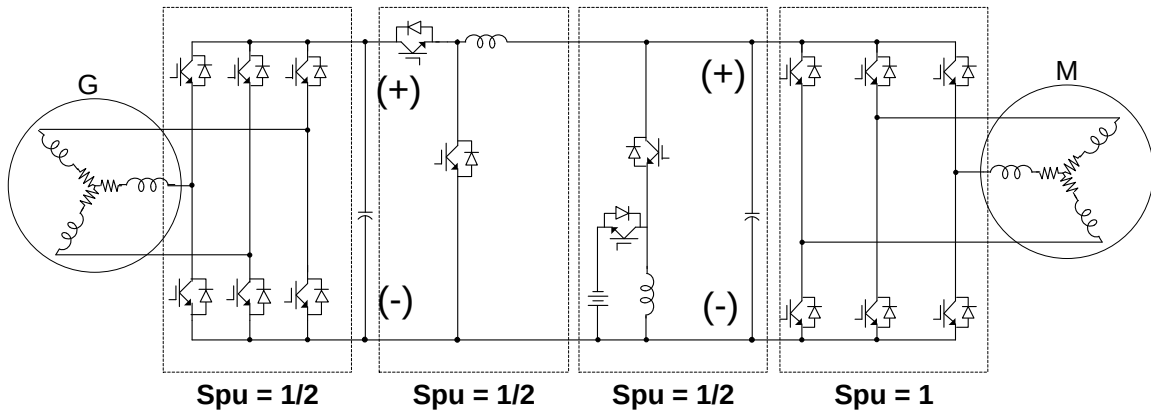


Figure 27 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter.

Per unit power flow through each inversion or conversion process is indicated.

Regarding power flow, only the generator power must flow through the first converter on the GI end and only the battery power must flow through the second (battery) converter. All system power must flow through the TI. Also with this topology, the buck-boost converter (connected to the battery) switching devices must be oversized as compared to a boost or a buck converter. The voltage seen across S_3 , and S_4 will be

$$V_{S3} = V_{S4} = V_{DC_GI} + V_{Batt} \quad (\text{eq 4.6})$$

The buck-boost converter allows the complete de-coupling of V_{DC_GI} from V_{DC_TI} , but this large voltage across S_3 and S_4 also causes significant switching losses.

4.5 VSI / VSI Structure, LV Battery, DC-Link with Integrated Magnetic Boost Converter Using Open Circuit Zero States of Inverter Phase Legs

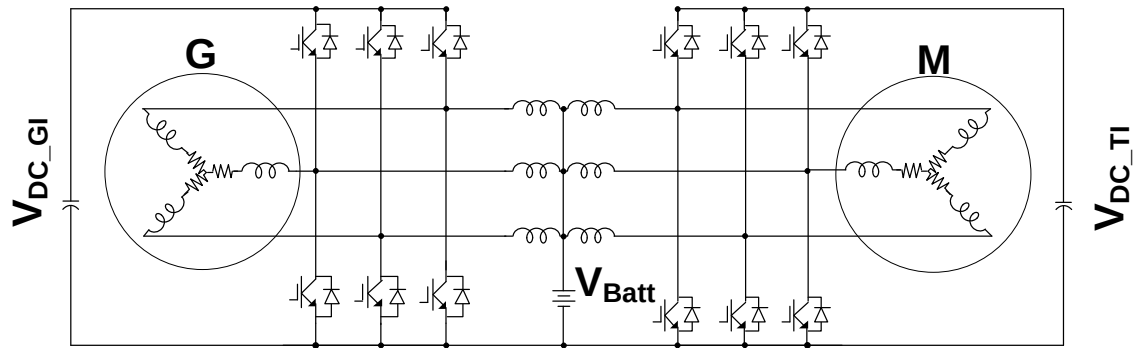


Figure 28 VSI / VSI Structure, LV Battery, DC-Link with Integrated Magnetic Boost Converter

Using Open Circuit Zero States of Inverter Phase Legs.

The topology shown in Figure 28 is also based upon the basic VSI / VSI configuration. The connection from the DC-Link voltage on the GI end is made via an integrated magnetic DC-DC converter. Likewise, the connection from to the DC-Link voltage on

the TI end is made in the same way. Theoretically, the GI DC-Link voltage could be controlled by controlling the open circuit zero states (OCZ) of the GI. Since the GI has to use both active states and OCZ states in its normal function to control the generator, the DC/DC conversion between the GI and the battery pack can use these zero states. The zero states are traditionally evenly divided between closing all three upper switches, for the open circuit zero state (upper zero state), or all three lower switches (lower zero state). By choosing which zero state to use, the DC-Link voltage could be controlled. When the upper switching devices are used to perform the zero state, the inductors see the following voltage.

$$V_L = V_{DC_GI} - V_{Batt} \quad (\text{eq 4.7})$$

And when the lower switches are used for the zero state, the inductor voltage is:

$$V_L = -V_{Batt} \quad (\text{eq 4.8})$$

As can be deduced, the power flow to and from the GI and battery can be controlled by controlling the duty cycles of the upper or lower zero state.

Voltage conversion from the battery pack to the DC-Link at the TI end uses the same method. Theoretically, the DC voltage at the TI can range as low as the voltage of the battery pack to infinity. This topology benefits from reduced components by not having a separate DC/DC converter.

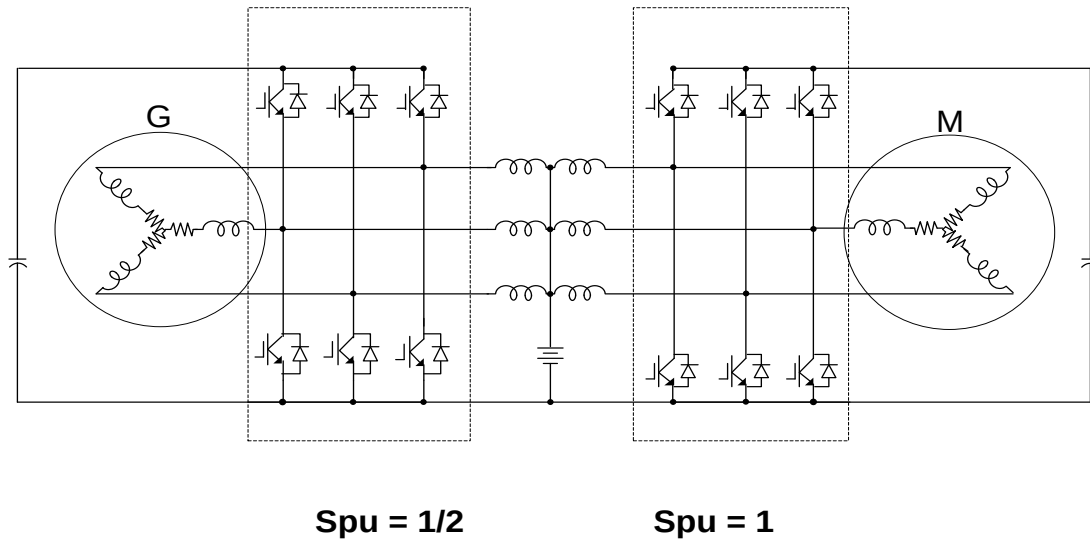
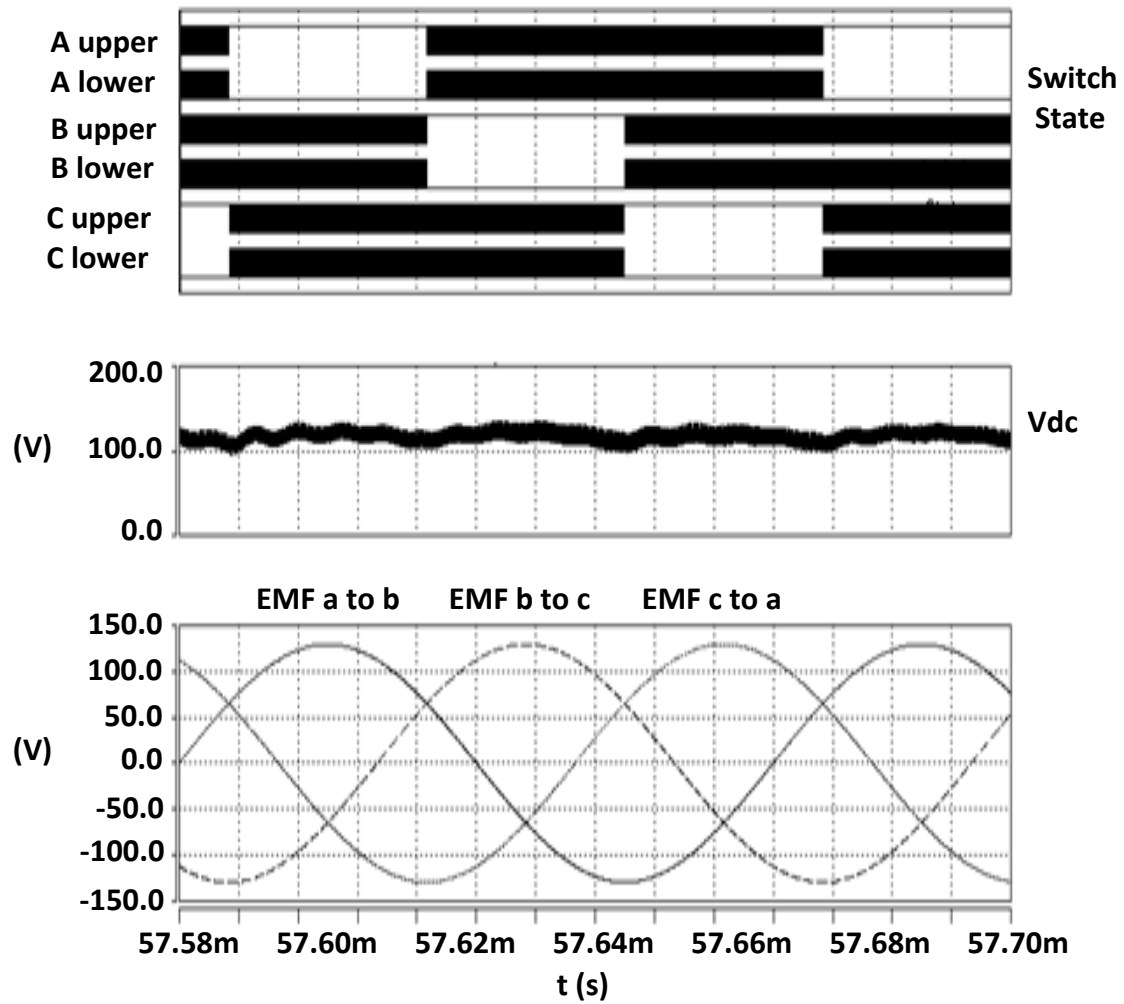


Figure 29 VSI / VSI Structure, LV Battery, DC-Link with Integrated Magnetic Boost Converter

Using Open Circuit Zero States of Inverter Phase Legs. Per unit power flow through each inversion or conversion process is indicated.

Only the power of the GI must flow through the left converter whereas both the battery power and the GI power must flow through the second converter. Below, in Figure 30, are some simulation results under the condition that only the upper open circuit zero state is being used. The first image shows switching states (phase “A” upper switch, phase “A” lower switch, ... ,phase “C” lower switch). The second image shows the back emf from the traction motor and the third image is the DC-Link voltage being held at 100V (the simulation battery voltage).

Figure 31 shows the same switching waveforms and DC-Link voltage with a zoomed in time frame.



**Figure 30 Inverter switching state, DC-Link voltage, and back EMF
of the VSI / VSI Integrated Magnetic topology
using only upper OCZ states. $V_{batt} = 100V$ in this simulation.**

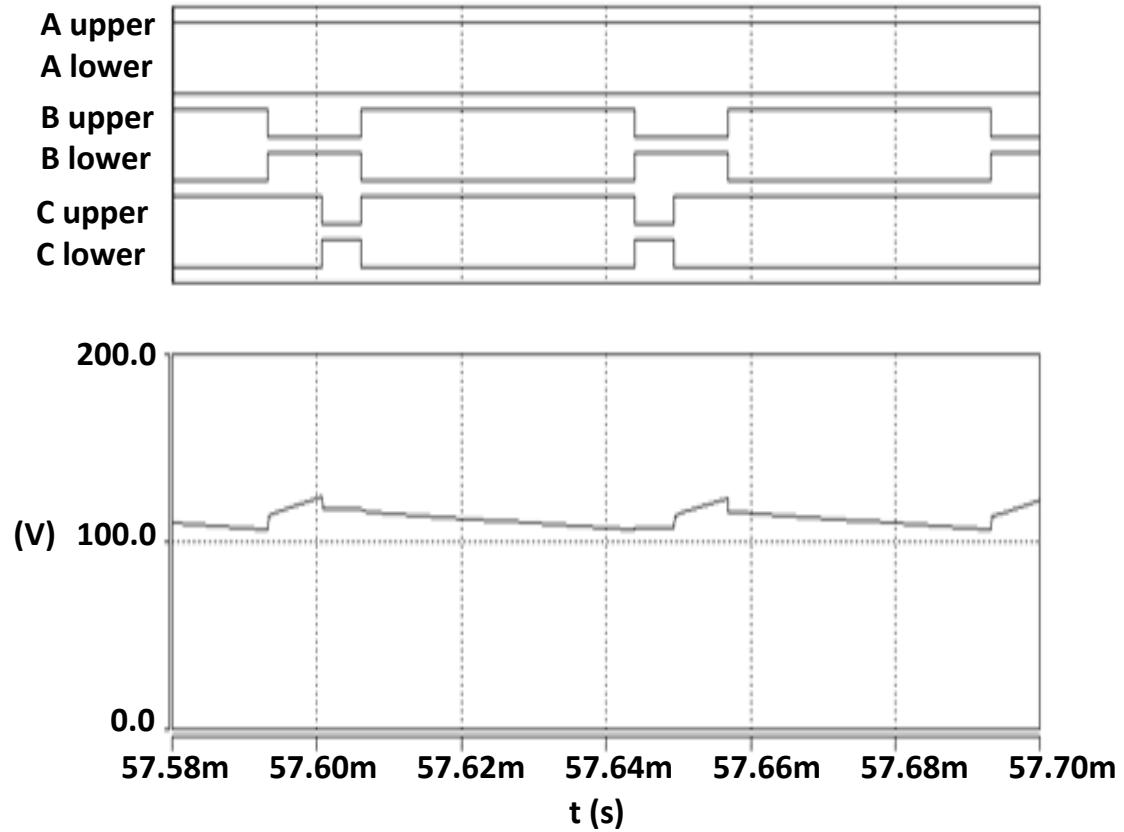


Figure 31. Switch states and DC-Link voltage.

Same conditions as Figure 30. Zoomed in on the time scale. High switch state = switch closed, low switch state = switch open.

This topology has some problems however. Notice that the line to line voltage of the motor and generator are across the boost inductors at all times. As such, the topology is not practical for low motor speeds. Therefore, this topology will be excluded from further study.

4.6 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converter

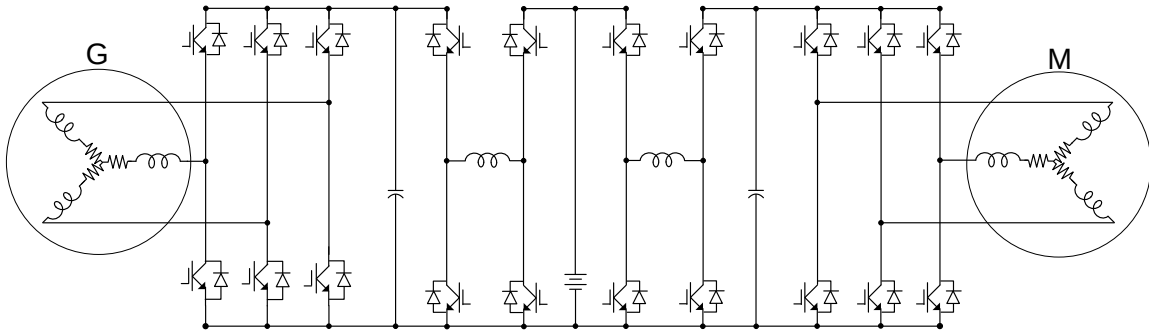


Figure 32 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converter

This configuration also is based on the traditional VSI / VSI structure, but with two buck-boost converters on the DC-Link. The buck boost converters are of an “H” bridge type. Each converter has four switches rather than the two switches of other designs; however, this buck-boost converter does not invert the polarity and the voltage stress on the switches is lower. With these two buck-boost converters, the voltage level at the TI end and GI end of the DC-Link are completely decoupled. The voltage level from the GI can be varied from zero to infinity (theoretically) and the same is true for the TI end of the DC-Link.

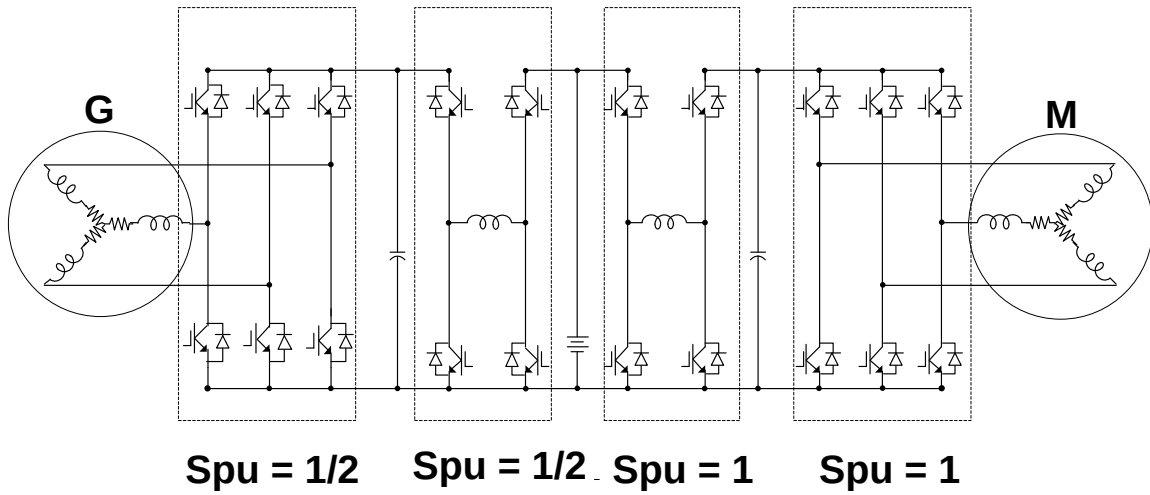


Figure 33 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converter.

Per unit power flow through each inversion or conversion process is indicated.

The left converter must conduct just the power flow of the generator while the second converter (on the right) must conduct both the generator power and the battery power (total system power). This topology has the advantage of being able to completely decouple V_{DC_GI} from V_{DC_TI} , but with the disadvantage of even more additional components.

4.7 Back to Back Current Fed Quasi-Z-Source Inverters, LV Battery

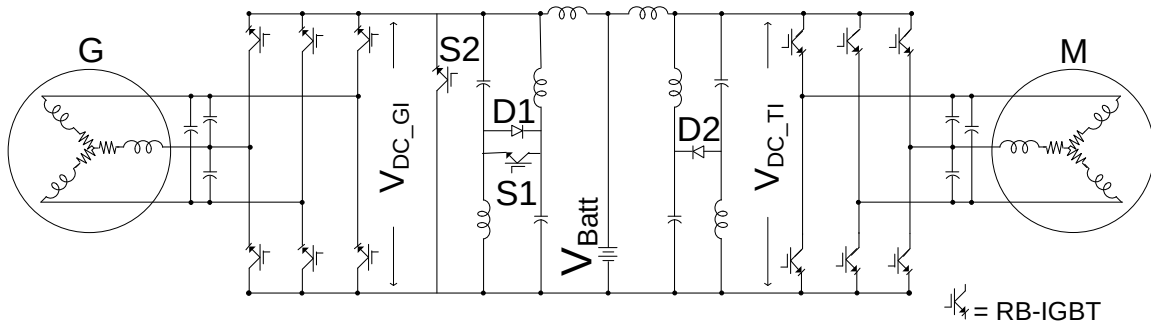


Figure 34 Back to Back Current Fed Quasi-Z-Source Inverters, LV Battery

Figure 34 shows the back to back current fed quasi “Z” source inverter topology. Notice that the GI and TI are using a reverse blocking IGBT. This device can block voltage in both directions but will allow current to flow in only one direction when gated on. It also uses the quasi-Z-source impedance network composed of two inductors and two capacitors. The quasi-Z-source impedance network on the generator end includes an IGBT module to allow power flow from the battery to the generator/starter motor to start the diesel engine. The impedance network on the TI end includes just a diode. More about the operation of this topology will be covered in the last chapter.

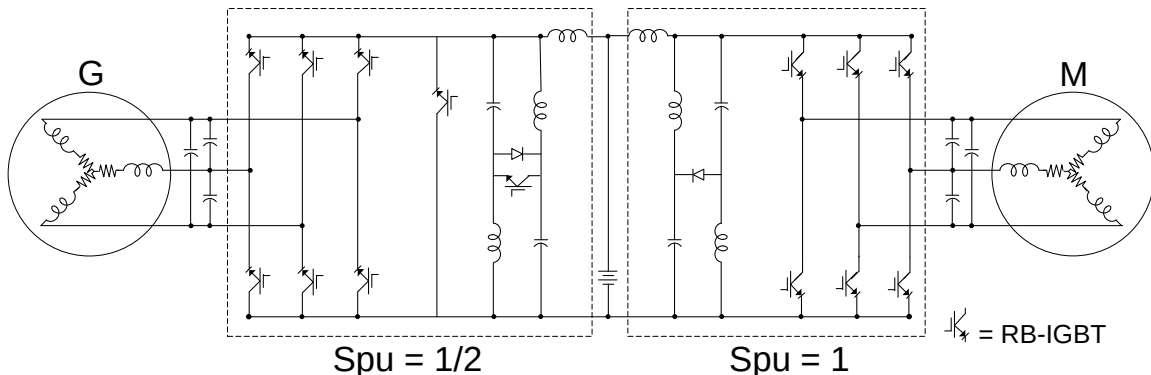


Figure 35 Back to Back Current Fed Quasi-Z-Source Inverters, LV Battery.

Per unit power flow through each inversion or conversion process is indicated.

The impedance network on the GI end of the topology only carries $\frac{1}{2}$ of the total system power and the corresponding impedance network on the TI end carries full system power. Also, this topology benefits from not having a separate DC/DC converter for the battery, but does have additional inductors, switching devices and switching states.

4.8 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery

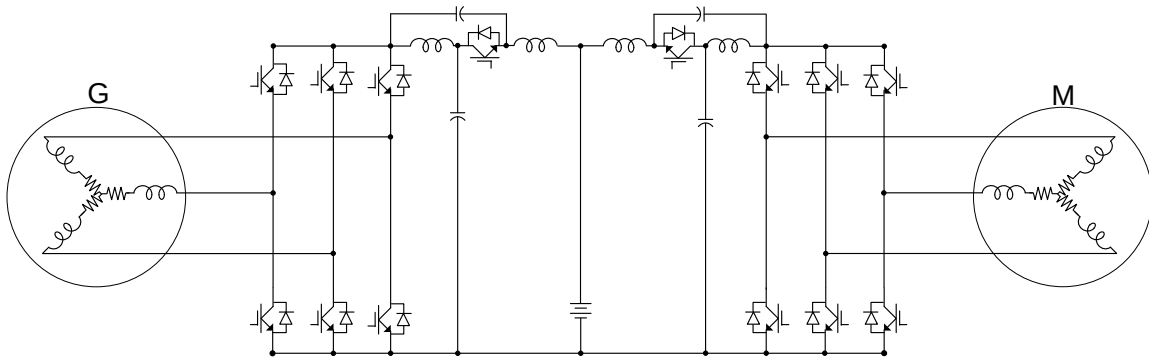


Figure 36 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery

This configuration is based upon the VSI / VSI topology with two voltage fed continuous current qZSIs added to the DC-Link. The left (generator) qZSI bucks the higher voltage at the generator end of the DC-Link down to the battery voltage, and boosts the lower battery voltage up to the voltage level at the generator end of the DC-Link. Likewise, the right (traction) qZSI can boost the voltage level at the traction inverter end of the DC-Link from the battery voltage up to the level needed for full speed operation of the bus. The voltage level at the generator end can be as high as is desired. The GI short circuit zero states buck the generator voltage down toward the battery. The DC-Link voltage at

the TI end can be controlled to range from the battery voltage to infinity (theoretically). The voltage level at the TI end of the DC-Link can be boosted via the short circuit zero states of the TI. The continuous current voltage fed qZSI can allow bi-directional power flow by using bi-directional current, unidirectional blocking switches such as shown in Figure 36. To flow power from the generator to the battery, the IGBT needs to be gated on. To flow power from the battery to the TI, the IGBT is gated open.

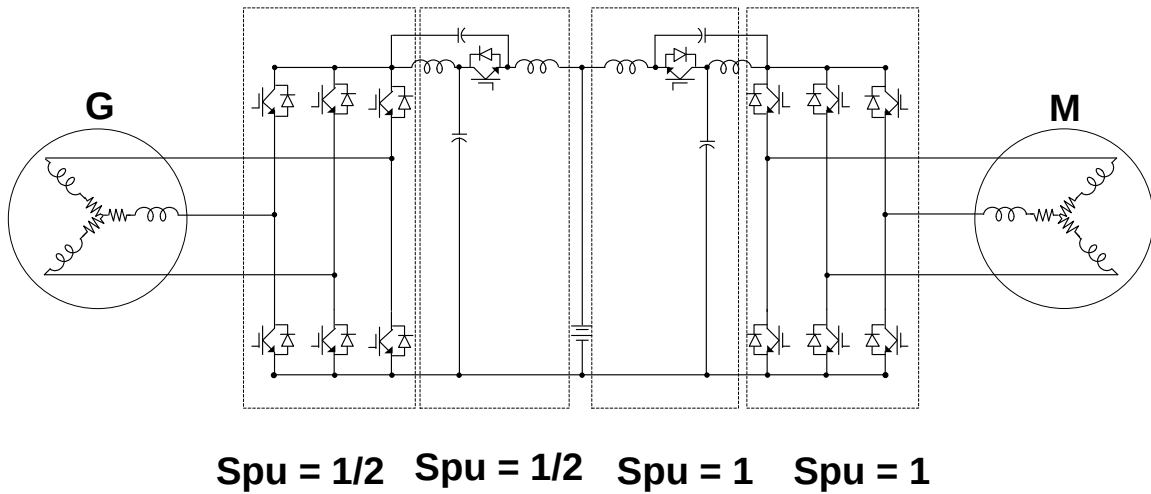


Figure 37 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery.

Per unit power flow through each inversion or conversion process is indicated.

Just the power flow from the GI flows through the left qZSI network, and both the battery power and the generator power flow through the right qZSI network. This topology also benefits from not needing a separate DC/DC converter for the battery, but has additional inductors, switching devices and switching states.

4.9 Summary of proposed topologies

The topologies shown in section 4.2 *VSI / VSI with “H” Bridge Coupled Battery Pack* and section 4.5 *VSI / VSI Structure, LV Battery, DC-Link with Integrated Magnetic Boost Converter Using Open Circuit Zero States of Inverter Phase Legs* have been shown to be dysfunctional in their present form. They will be excluded from the analysis in the following section. The various topologies presented are able to decouple the voltages to lesser or greater degrees. Some are able to completely decouple the voltage and others are able to achieve a variable voltage at the TI that varies from the battery voltage up to the max. Each topology has its own pros and cons regarding the distribution of power flow through components, voltage stresses seen by switching devices during the open state and switching transition, additional inductors, presence or absence of battery DC/DC converter, and additional switching states. These factors will all be analyzed in the following section.

5. LOSS ANALYSIS OF SELECTED TOPOLOGIES

This section presents analytical results of the new topologies. Of the topologies that were introduced in chapter 4, those which are functional are considered here in more detail. The losses of switching devices in the inverters and converters as well as the inductor losses are calculated in the following sections. Capacitor losses are ignored in this study because the capacitor losses of the traditional topology (which provides the base line or point of comparison) are essentially equivalent to the capacitor losses in the new topologies and therefore can be neglected in this comparative study. The next section describes the formation of the comparative base line.

5.1 Base Line:

First, the efficiency of the traditional hybrid bus topology will be analyzed to form a base line against which other topologies proposed in this paper can be compared. Turn on loss, P_{on} , turn off loss, P_{off} , IGBT conduction loss, P_i , Diode conduction loss, P_d , and diode reverse recovery loss, P_{rr} , of the inverters and converter were calculated in a manner similar to that in [25].

5.1.1 Evaluation of Efficiency of the topologies.

The equations used to calculate the efficiencies of the topologies were briefly referred to before, and are discussed more thoroughly here. Figure 38 **Error! Reference source not found.** below shows the voltage and current of a typical semiconductor switching device during the turn on transient, conduction, and turn off transient. Notice near the left end of the picture, that while the collector current (I_C) of the IGBT is increasing, that the

voltage across the IGBT remains high. This is the turn on transient of the device. It is the presence of the current through the device and the simultaneous voltage across the device that causes a power loss. The time period, t_r , is the rise time for the current which results in the turn-on switching losses. Since the voltages and currents are changing, the product of these values must be integrated during this time period to calculate the energy lost. Also, we desire to cumulate the switching losses during a fundamental power cycle and average them to find the rate of energy loss known as power loss. This must be done for the turn-off transient during t_f , and for the conduction period between t_r and t_f . In general, the fundamental power cycle of the inverters can be found by following the sinusoidal current. The DC/DC converter requires different equations since their power flow does not follow a sinusoidal current waveform. Also, the Z-source type topologies have additional switching states (short circuit zero or shoot-through) that must be considered.

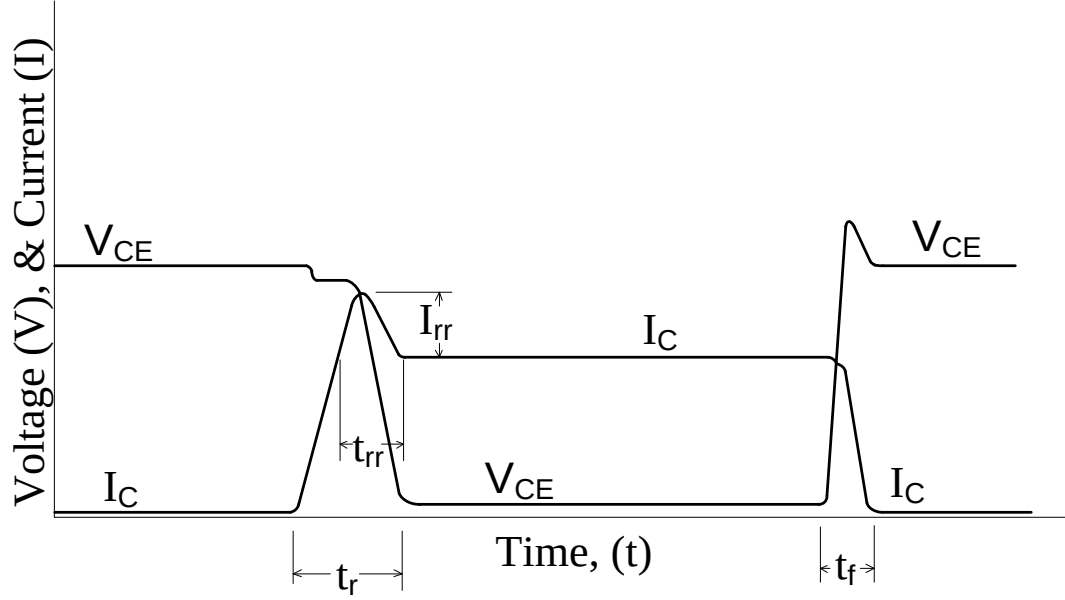


Figure 38. Voltage and current waveforms of a typical semiconductor switching device

The loss comparison between the new topologies and the traditional topology were calculated using the following equations as taken from [25].

$$P_{on} = \frac{1}{8} V_{cc} \cdot t_{rN} \frac{I_{cM}^2}{I_{cN}} F_s \quad (5.1)$$

$$P_i = \left(\frac{1}{8} + \frac{M}{3\pi} \cos(\theta) \right) \frac{V_{ceN} - V_{co}}{I_{cN}} I_{cM}^2 +$$

$$\left(\frac{1}{2\pi} + \frac{M}{8} \cos(\theta) \right) V_{co} I_{cM} \quad (5.2)$$

$$P_d = \left(\frac{1}{8} - \frac{M}{3\pi} \cos(\theta) \right) \frac{V_{FN} - V_{Fo}}{I_{cN}} I_{cM}^2 +$$

$$\left(\frac{1}{2\pi} - \frac{M}{8} \cos(\theta) \right) V_{Fo} I_{cM} \quad (5.3)$$

A slight modification is made to the equations found in [25] for P_{off} and P_{rr} as was

necessary for this particular case. The equations used for P_{off} and P_{rr} are presented just below.

$$P_{off} = V_{cc} \cdot I_{cM}^2 \cdot t_{fN} \cdot F_s \left(\frac{1}{8 \cdot I_{cN}} \right) \quad (5.4)$$

$$P_{rr} = F_s V_{cc} \left[\left(0.1404 + \frac{0.1902}{\pi} \frac{I_{cM}}{I_{cN}} + 0.0075 \left(\frac{I_{cM}}{I_{cN}} \right)^2 \right) * \right. \\ \left. Q_{rrn} + \left(0.05 \frac{I_{cM}}{I_{cN}} + \frac{0.8}{\pi} \right) I_{cM} \cdot t_{rrN} \right] \quad (5.5)$$

where:

P_{on} is the IGBT turn on loss,

P_{off} is the IGBT turn off loss including tail current loss,

P_i is the IGBT conduction loss ,

P_d is the freewheeling diode conduction loss,

P_{rr} is the diode reverse recovery loss,

V_{cc} is the dc-link voltage,

t_{fN} is the rated rise time,

I_{cM} is the maximum collector current,

I_{cN} is the rated collector current,

F_s is the switching frequency,

M is the modulation index,

θ is the power factor angle,

V_{ceN} is the rated voltage between the collector and emitter,

V_{co} is the threshold voltage between the collector and emitter,

V_{FN} is the rated diode forward voltage,

V_{F0} is the threshold diode voltage,

t_{fN} is the rated fall time,

Q_{rrN} is the rated recovery charge.

These variables can be taken directly from IGBT module specification sheets. The equations used to calculate the switching losses of the traditional configuration's dc/dc converter are:

$$P_{on} = \frac{1}{2} \cdot V_{cc} (I_{dc})^2 \frac{t_{rN}}{I_{cN}} F_{sdc} \quad (5.6)$$

$$P_{i_DC} = \left[\left(\frac{V_{ceN} - V_{c0}}{I_{cN}} I_{dc} + V_{c0} \right) \right] I_{dc} \quad (5.7)$$

$$P_{off} = \frac{1}{2} V_{cc} (I_{dc})^2 \cdot \frac{t_{fN}}{I_{cN}} \cdot F_{sdc} \quad (5.8)$$

$$P_{tail_DC} = \frac{3}{80} V_{cc} I_{dc} t_{tail} F_{sdc} \quad (5.9)$$

$$P_{d_DC} = \left[\left(\left(\frac{V_{FN} - V_{F0}}{I_{cN}} \right) I_{dc} + V_{F0} \right) I_{dc} \right] \quad (5.10)$$

$$P_{rr_DC} = V_{cc} t_{rrN} \left[I_{dc}^2 \left(0.045 \frac{i_{rrN}}{I_{cN}^2} + \frac{0.3}{I_{cN}} \right) + \right. \\ \left. I_{dc} \left(0.225 \frac{I_{rrN}}{I_{cN}} + 0.8 \right) + 0.281 I_{rrN} \right] F_{sdc} \quad (5.11)$$

Where I_{dc} is the DC current flowing through that device, and this depends upon which side of the converter the devices is on (high voltage or low voltage side), and F_{dc} is the switching frequency of the DC/DC converter.

Inductor loss was approximated by the following equation 5.13 which has provided a reasonable loss approximation for inductors tested in the lab.

$$P_{ind_dc/dc} \approx P_{dc} \left(\left| 0.0043(B_{dc/dc} - 1) \right| + 0.0057 \right) \quad (5.13)$$

Where:

$P_{ind_dc/dc}$ is the power loss in the DC/DC converter inductor

P_{dc} is the DC power being absorbed or provided by the battery pack

$B_{dc/dc}$ is the boost factor of the DC/DC converter.

For inductors sized and designed for the relevant power levels of this study, this equation has provided more accurate and slightly higher loss values than those of the Steinmetz equation. Therefore, by using equation 5.13, we err on the side of caution. This means that in the comparisons that follow, actual results of the new topologies will be slightly better than indicated by our conservative graphs.

For the comparison, a common set of conditions must be followed for both the new and traditional topology. The conditions for the comparison are as follows.

Conditions:

- Generator line-to-line voltage is 429 Vrms;
- rectified generator voltage is 700 Vdc;
- TM line-to-line voltage sweeps from 29 Vrms to 429 Vrms;
- switching frequency is 10 kHz;
- power factor is 90%;
- battery pack voltage is 350 Vdc;
- switching, conduction and reverse recovery losses are based upon a typical 1200-V/ 450-A IGBT, and diode, or a reverse blocking IGBT (RB-IGBT) as applicable.
- For the traditional topology in figure 1, the TI voltage is at all times held equal to the GI voltage of 700 Vdc while the TI voltage of the proposed topologies vary to the extent disclosed in the specific topology's section below.

5.1.2 Experimental Results

Before a base line is calculated, some experimental results are desired to confirm the concept and to verify the validity and accuracy of the loss equations. To achieve these

results, a DC-Link, a traction inverter and a traction motor were required. Toward these ends, a rectifier and inverter were built each using a 6MBI450U4-120 IGBT module six pack which is rated for 1200V and 450A. The rectifier used just the diodes of the six pack as a passive rectifier. The inverter also included a custom built gate drive and gate drive power supply, and both the inverter and rectifier has a 510 micro Farad capacitor bank. The inverter also has HTB 200-P current sensors on the phase “A” and “B” conductors and a LM25-P voltage sensor on the DC-Link. The motor being used as the traction motor is an interior permanent magnet AC motor (IPMAC) which was connected to a chassis dynamometer. In this case, the vehicle on the chassis dyno. is the load and the IPMAC motor connected to the chassis dyno. will function as our traction motor. A TMS320F28035 DSP board loaded with an adapted field oriented control program was used to control the motor. The digital signal processor (DSP) board was connected to the inverter via an optocouple board, and signal conditioning circuit boards for the current sensors, voltage sensor, and rotor position sensor. The experimental set up schematic and pictures are shown below.

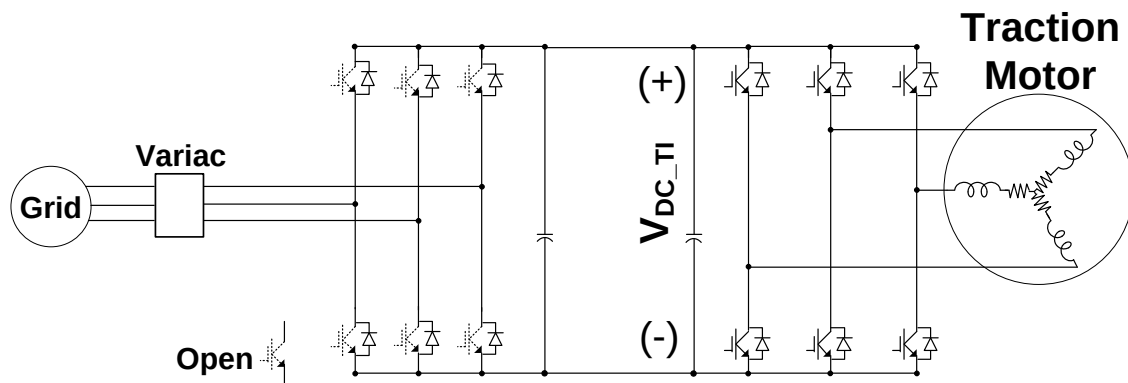
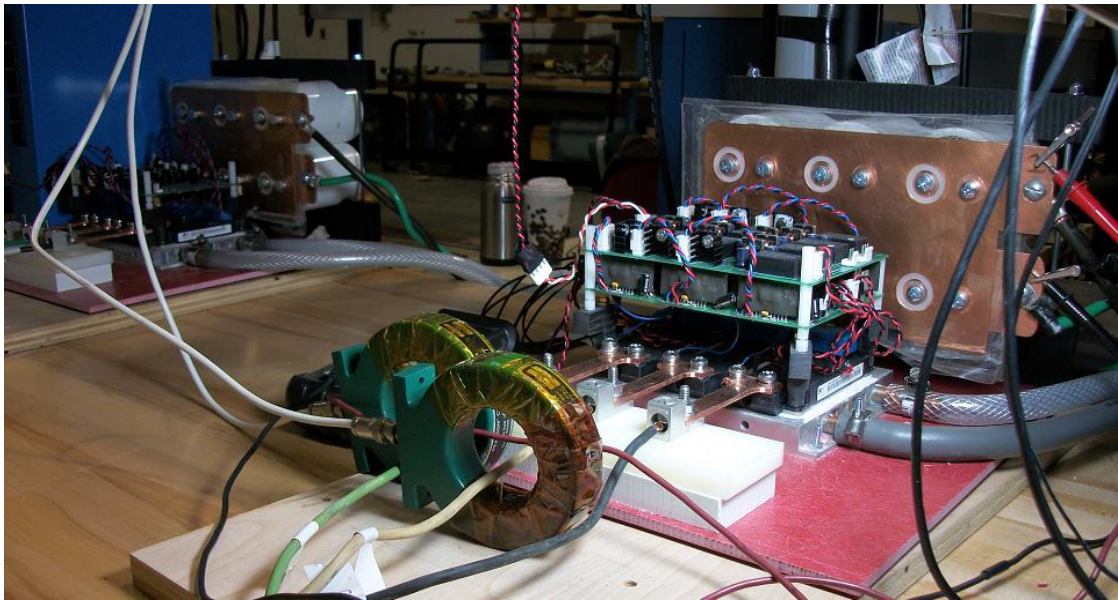


Figure 39. Experimental set up schematic diagram



(a) Rectifier on the left and inverter on the right.



(b) Variac

Figure 40 Experimental Setup

One of the adaptations required for the field oriented control algorithm is the addition of DSP board inputs for the rotor position signal. The rotor position sensor is made up of three coils wound on part of the stator. One coil is the excitation coil and two coils are the sensor coils that are coupled to the excitation signal based upon the saliency of the rotor and the location of the sensor coil. The two sensor coils are located 90 electrical degrees apart from each other. Their output is a rotor position amplitude modulated signal as in Figure 41.

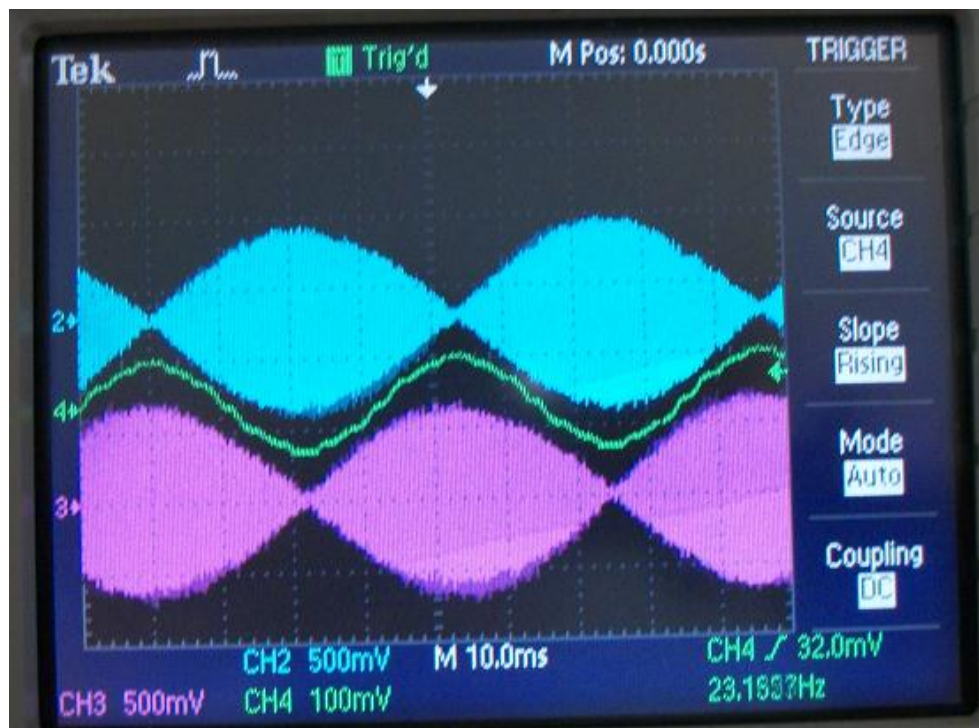


Figure 41 Amplitude modulated rotor position signals.

A high frequency signal is injected into the stator and this signal is modulated by the saliency of the rotor. The middle waveform is the line to line back emf of phase “a” to “b”.

The upper waveform and lower waveform are the modulated signals where the high frequency signal is not discernible (appears opaque) in the above image due to the

frequency and time scale being used. The time scale was set so that the low frequency modulated part of the waveform could be seen. Also notice in the image, the middle waveform is the line to line back emf voltage of phase “a” to “b”. Shown in Figure 42 is the resultant $\sin(\theta)$ and $\cos(\theta)$ waveforms which are the result of applying trigonometric identities to the waveforms in the DSP and then applying a software low pass filter.

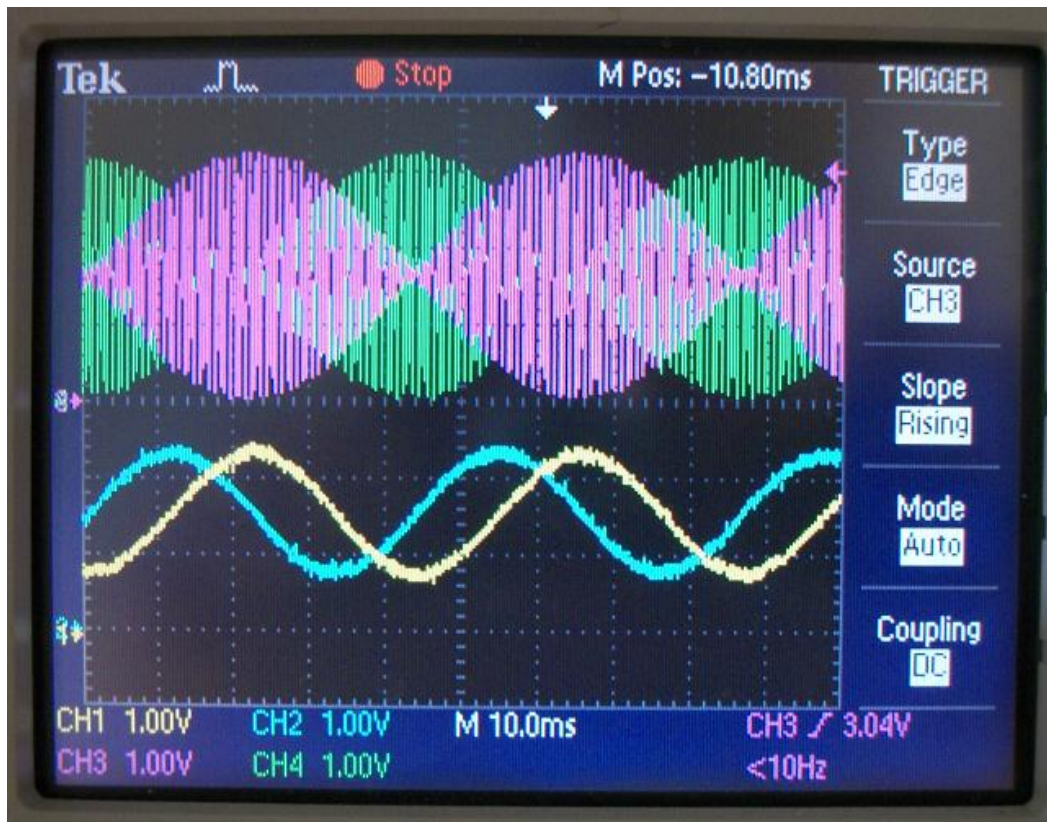


Figure 42 Amplitude modulated rotor position signals

(top two signals) and the resultant $\cos(\theta)$ and $\sin(\theta)$ rotor position signals (bottom two signals) where θ represents the rotor position.

The lower two sinusoids are shown here prior to being scaled for the DSP so that the positive sinusoid peak = 3.3V and the lower peak = 0V. Once the signals were properly scaled and phase shifted (due to the software filter), there is no need to find the value of θ

since the Park transform uses $\sin(\theta)$ and $\cos(\theta)$ as elements of its matrix. With this being the case, it is very convenient to simply input the above signals directly into the Park transform matrix. Once the motor was operating correctly, operating points could be achieved and the power loss of the inverter could be measured. For each motor operating point to be measured, a high voltage DC-Link and a low voltage DC-Link measurement were taken. A Yokogawa WT-1600 Power meter was used to measure the voltages, currents, and calculate the power and efficiency of the inverter. Below in Figure 46 are the results of these operating point's measured losses and calculated losses.



Figure 43 Chassis Dyno. used to obtain experimental results.

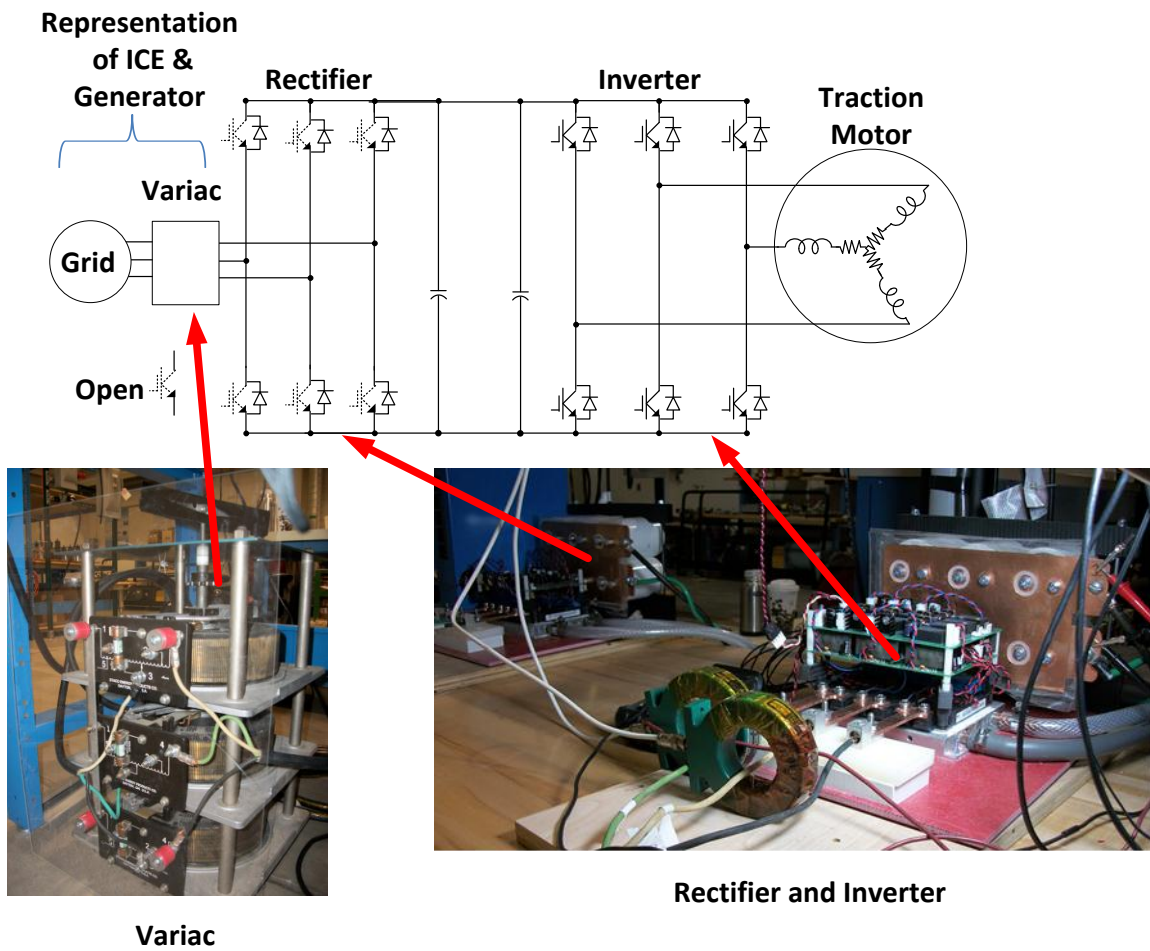


Figure 44 Experimental Setup

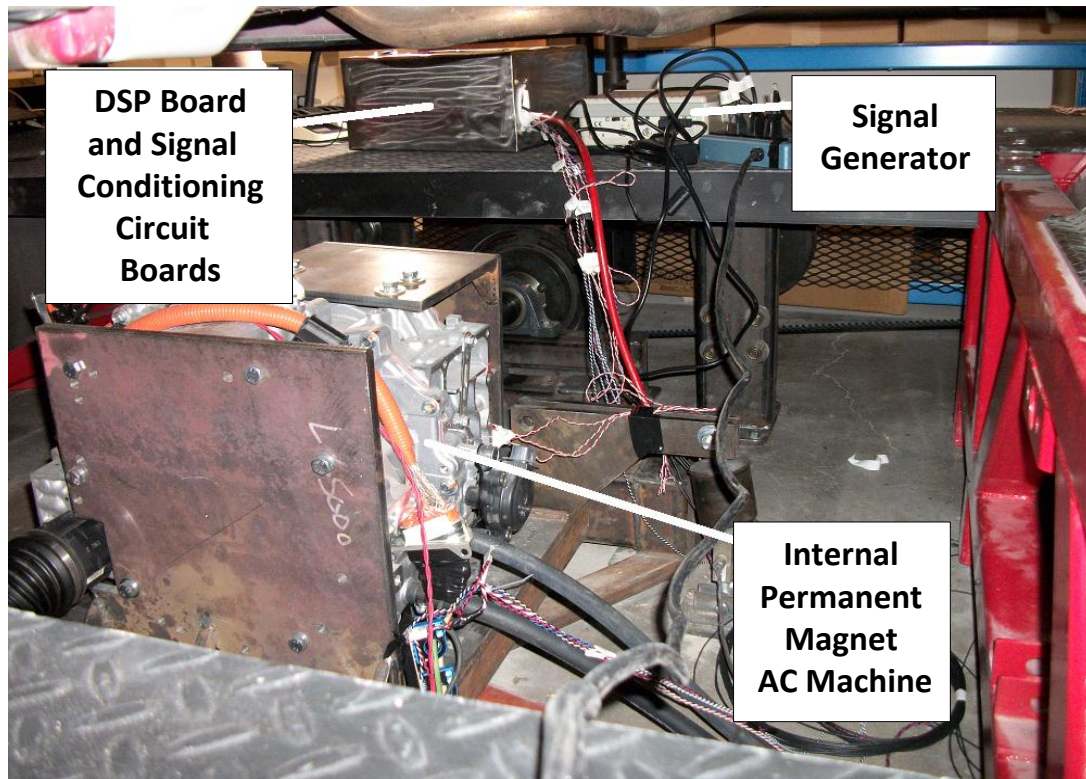


Figure 45 More of the experimental setup.

These items are located below the vehicle that is on the chassis dyno.

Vehicle velocity	2.6 MPH		5.0 MPH		7.7 MPH		10.0 MPH	
V_{dc}	98	440	197	444	292	431	305	427
P_{dc}	1,911	2,330	3,558	3,398	5,354	5,838	5,382	5,871
P_{ac}	1,751	1,808	3,294	2,919	5,076	5,386	5,099	5,470
P_{loss} (Measured)	160	433	264	479	278	452	283	401
P_{loss} (Calculated)	155	420	237	430	321	436	311	407

Figure 46 Experimental results showing four operating points

each with a high voltage result and a low voltage result. Actual losses and calculated losses are also shown.

Based upon these results, it can be seen that the high voltage DC-Link case does produce higher losses in the traction inverter. Also, the measured and calculated losses show good correspondence which lends credibility to the equations being used to calculate the losses of the new topologies to be analyzed in the next section.

5.1.3 Base Line Continued

The total range of operating points for the hybrid vehicle is very wide. The bus speed can range from 0 mph to 75 mph and the traction motor torque can range from a large negative value to a large positive value for all bus speeds. Also, the choice can be made to draw power from the ICE and generator, from the battery pack, or some combination of the two. The input to the hybrid vehicle's operating point decision model are gas pedal or brake pedal position, bus speed, and battery state of charge (SOC). For any given bus driver pedal position input, which corresponds to a requested positive or negative traction motor(TM) torque, there is an infinite combination of generator and or battery power levels from which to choose from. For this analysis, a reasonable range of such operating points was sought so that a fair comparison could be made.

To illustrate a representative set of operating points, the traction motor power was swept from 16.7kW to 250kW while holding the traction motors at full current. This represents full acceleration which is normal for these heavy vehicles. Full acceleration, or wide open throttle (WOT), for the typical automobile yields approximately a 0.5g acceleration.

Given that the typical automobile has a powertrain capable of 110kW and the bus powertrain is approximately twice this value, yet has 10 times more mass, we have:

$$F = ma \quad (5.14)$$

$$\frac{F}{m} = a \quad (5.15)$$

$$\frac{F_a}{m_a} = a_a = 0.5(g) \quad (5.16)$$

$$F_b \approx 2F_a \quad (5.17)$$

$$m_b \approx 10m_a \quad (5.18)$$

$$\frac{2}{10} \frac{F_a}{m_a} = a_b = 0.1(g) \quad (5.19)$$

Where:

F = force

m = mass

a = acceleration

F_a = Force of an automobile at WOT

m_a = mass of an automobile

a_a = acceleration of an automobile

F_b = force of a bus

m_b = mass of a bus

a_b = acceleration of a bus

As shown above, it can be seen that WOT acceleration for the bus is a rather mild acceleration of 0.1g. Additional analysis was done in this work at throttle positions other than WOT and as can be deduced after further reading, very similar results were observed.

For the sweep of TM operating points, three different scenarios will be shown:

Scenario 1 holds the generator power steady at 50kW throughout the TM power sweep while the battery pack provides or absorbs the difference in power between the generator power and TM power;

Scenario 2 holds the generator power steady at 100kW while, again, the battery makes up the difference, and

Scenario 3 holds the generator power steady at 150kW and again, the battery pack makes up the difference.

Figure 47 shows this power sweep for the traditional hybrid topology.

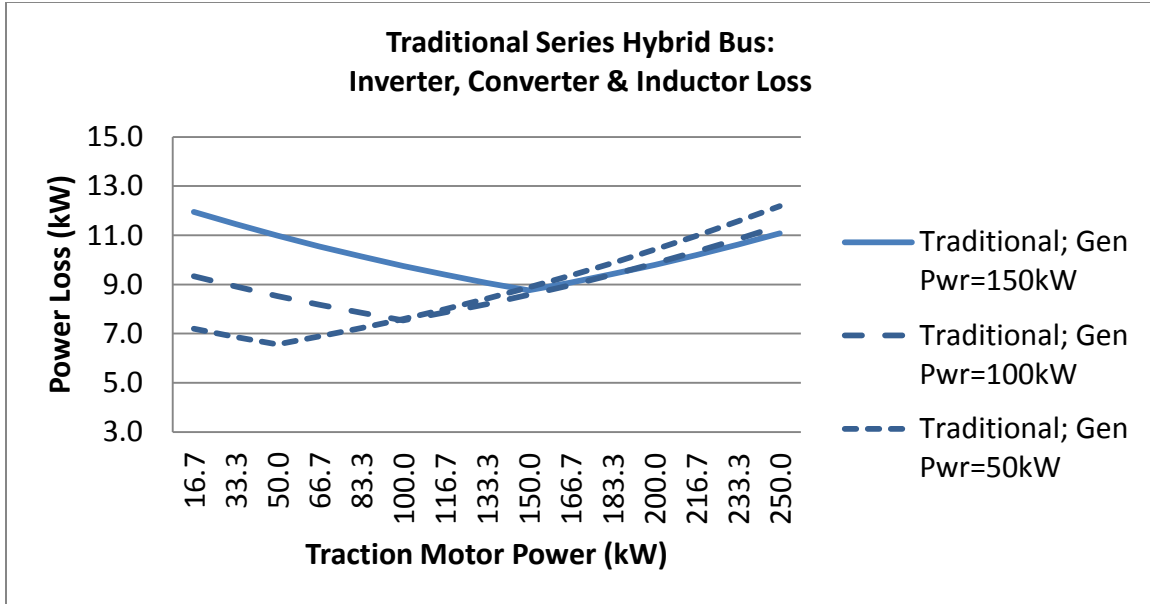


Figure 47. Power loss curves for the traditional back to back VSI/VSI series hybrid bus.

Now that the base line data has been completed, the proposed topologies can be investigated.

5.2 Proposed Topologies

Several new topologies are proposed below. Each topology is an attempt to decouple the DC voltage at the GI end of the topology from the DC voltage at the TI end. The power losses of the following topologies have been calculated in the same manner as the base line except that the voltage at the TI can be different from the GI voltage. Also, any additional converter and their related switching states and or components (inductors for example) are also included in the loss calculations. The same three scenarios are assumed here as well.

5.2.1 VSI / VSI with Conventional Mid-Link DC / DC Boost Converters

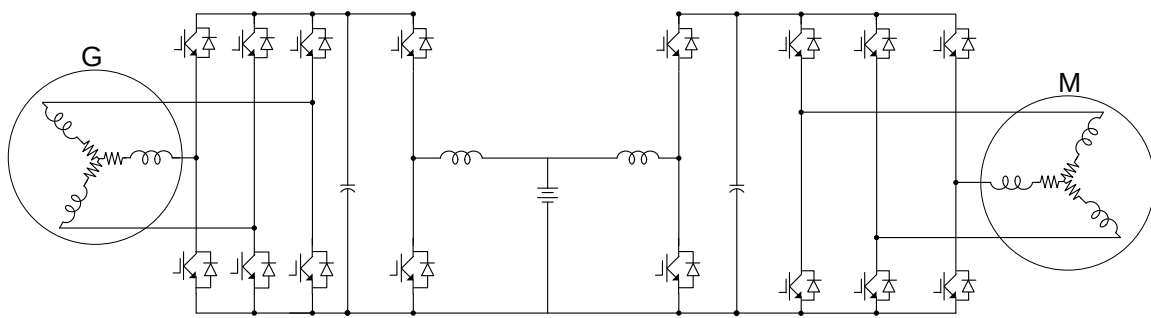
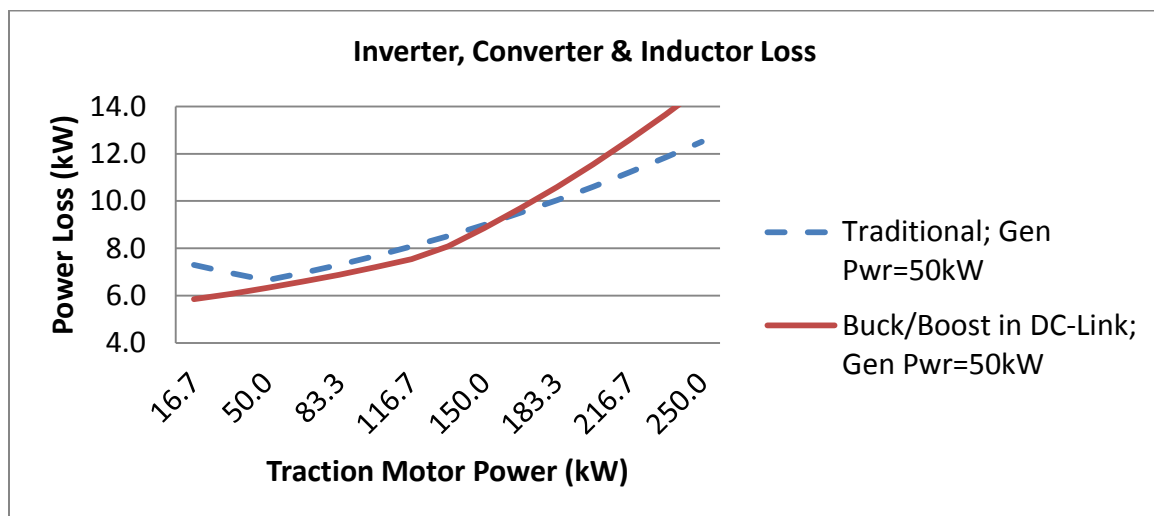


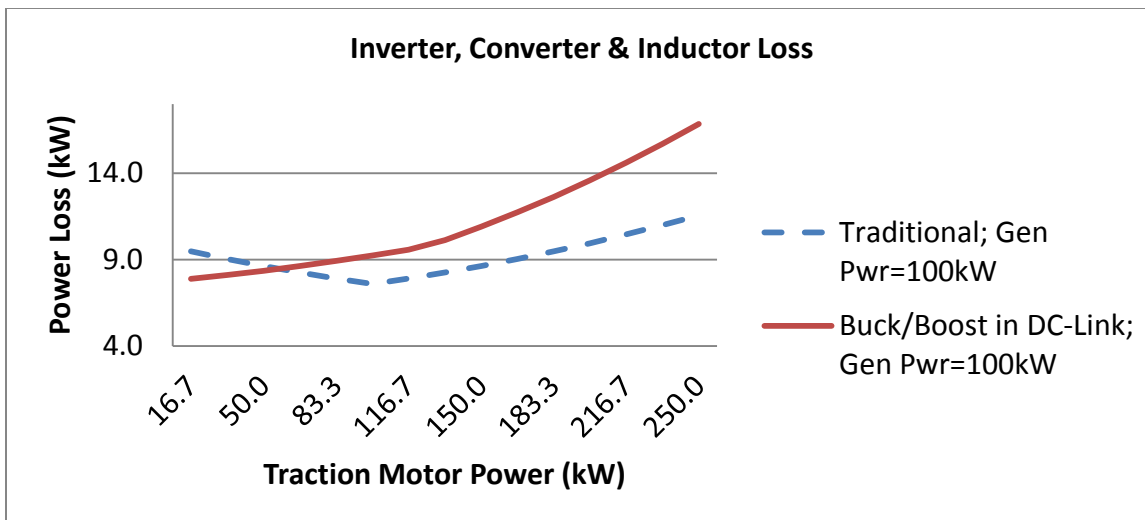
Figure 48 Back to back VSI to VSI with boost converters in the DC-Link



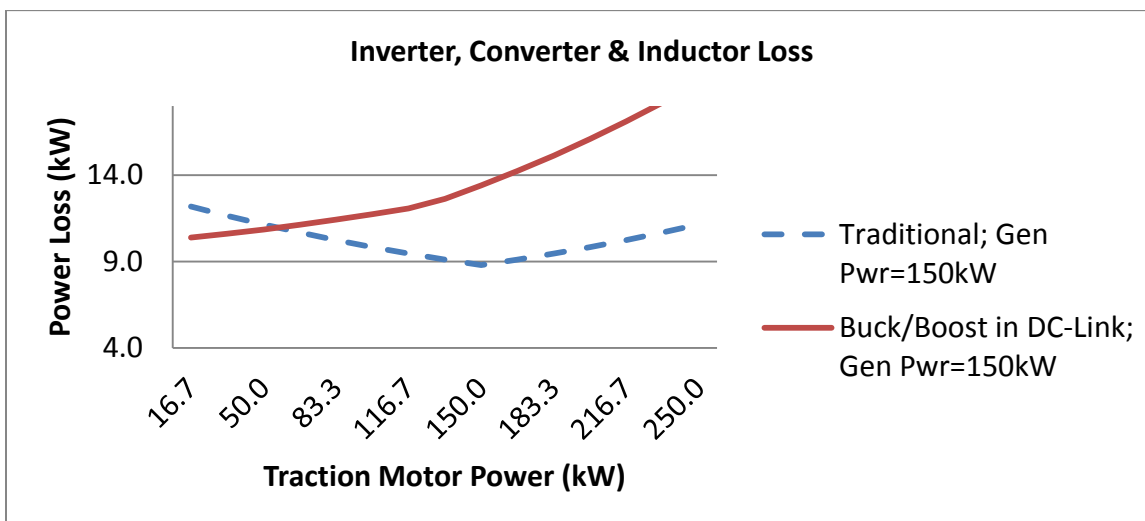
(a) Scenario 1. Generator held at 50kW.

Figure 49 Loss graphs (a, b, and c) for the Back to back VSI to VSI with boost converters in the DC-Link

Figure 49 continued



(b) Scenario 2. Generator held at 100kW.



(c) Scenario 3. Generator held at 150kW.

5.2.2 VSI / VSI Structure, LV Battery with Boost Converter, & DC-Link with Buck Converter

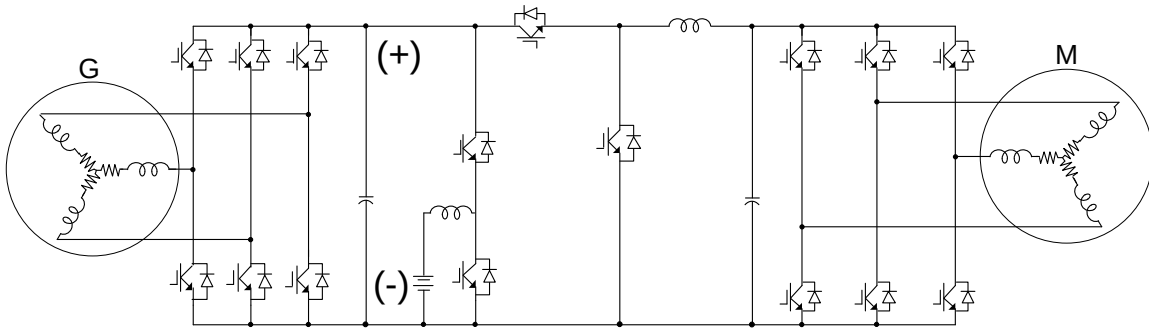
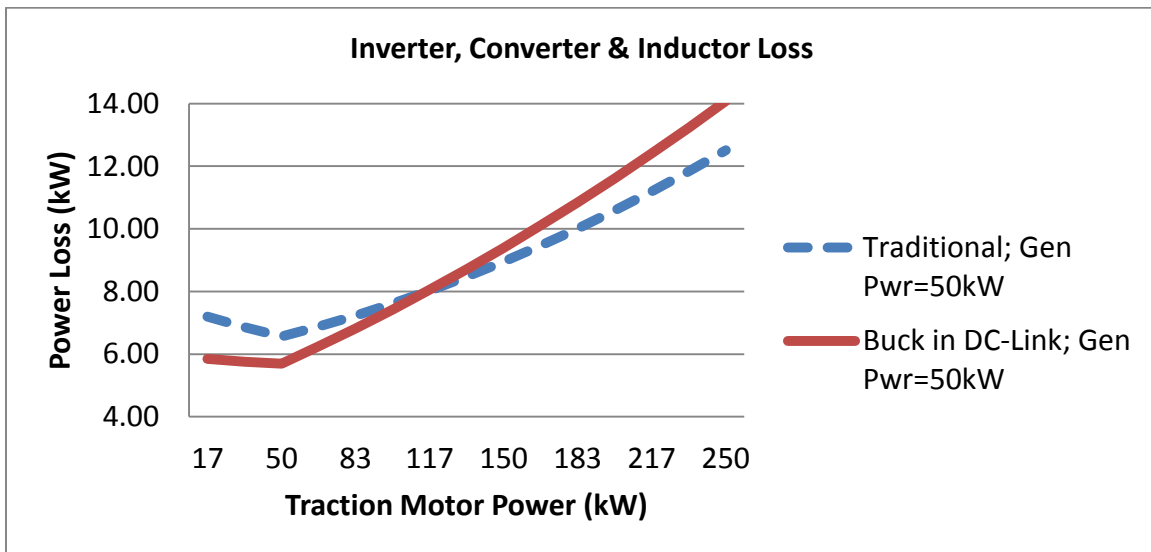


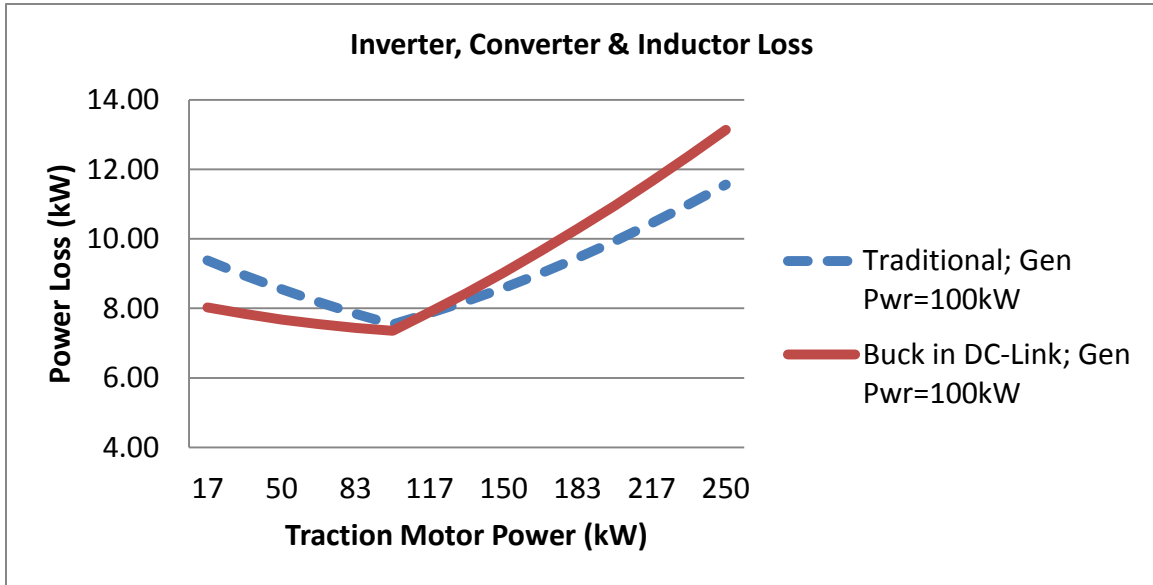
Figure 50 Back to back VSI / VSI topology with battery boost converter and TI DC-Link buck converter.



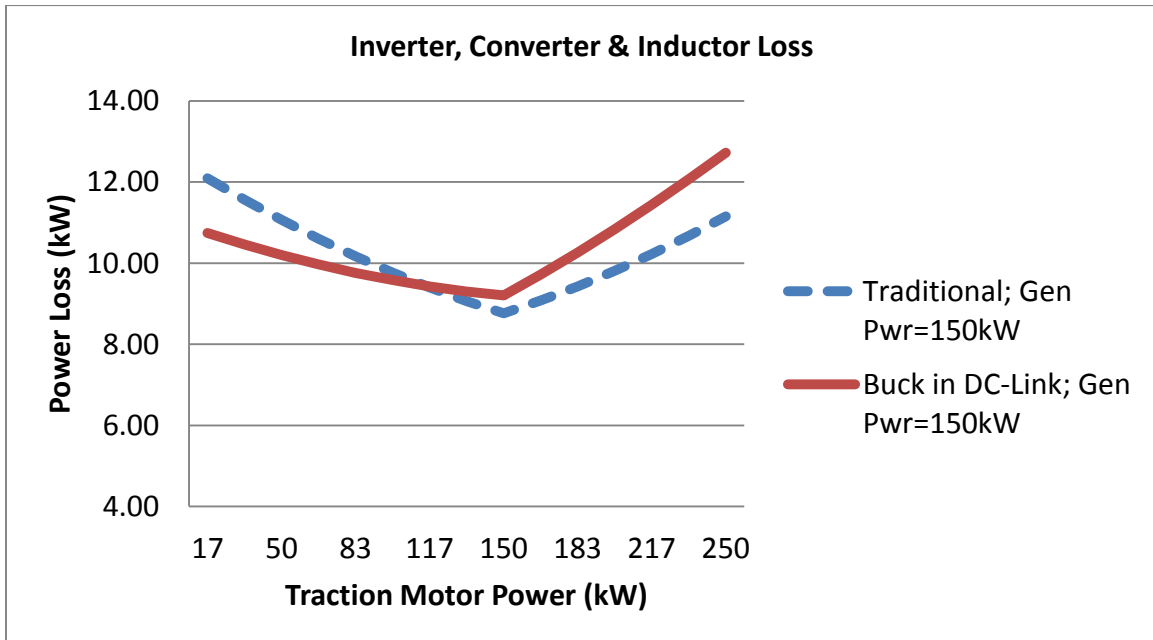
(a) Scenario 1. Generator held at 50kW.

Figure 51 Loss graphs (a, b and c) for the Back to back VSI / VSI topology with battery boost converter and TI DC-Link buck converter.

Figure 51 continued



(b) Scenario 2. Generator held at 100kW.



(c) Scenario 3. Generator held at 150kW.

5.2.3 VSI / VSI Structure, LV Battery with Buck-Boost Converter, & DC-Link with Buck Converter

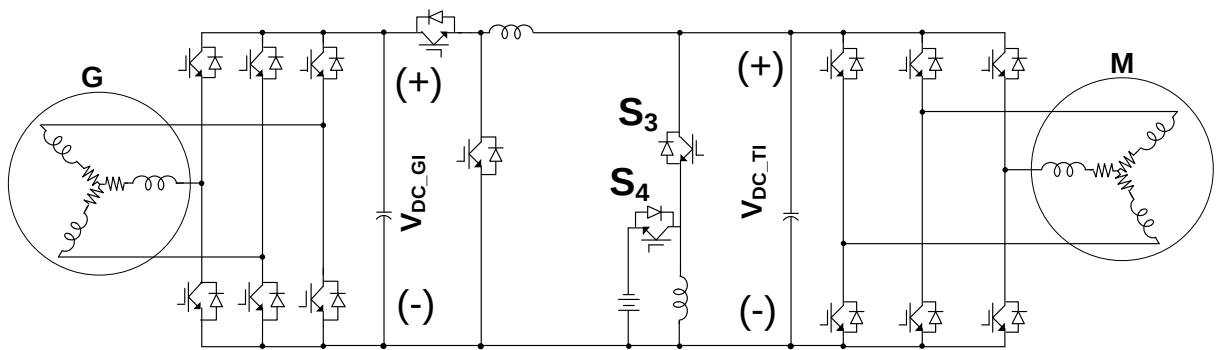


Figure 52 Back to back VSI / VSI topology with battery buck-boost converter and GI DC-Link buck converter.

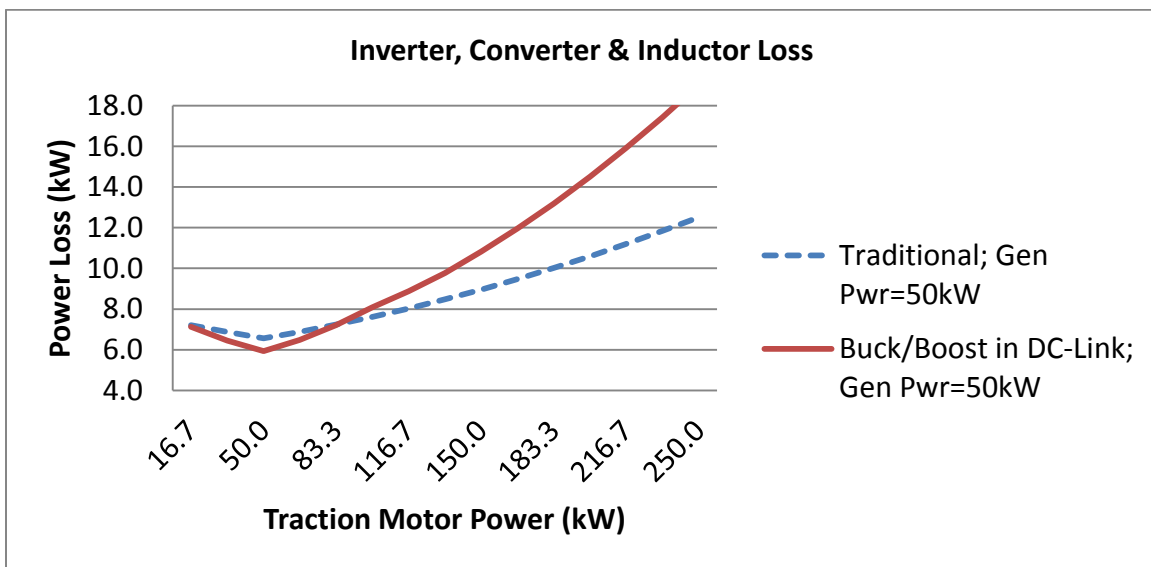


Figure 53 Loss graphs under scenario one conditions (Generator at 50kW) for the Back to back VSI / VSI topology with battery buck-boost converter and GI DC-Link buck converter.

Since this topology does not provide significant savings, only the 50kW case is displayed.

5.2.4 VSI / VSI Structure, LV Battery, DC-Link with Bi-Directional Buck and Boost Converters

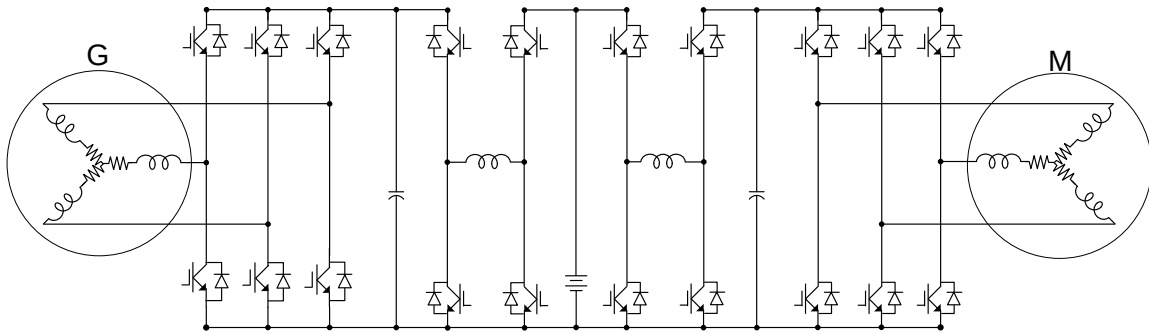


Figure 54 Back to back VSI / VSI topology with GI bi-directional buck-boost converter and TI bi-directional buck-boost converter.

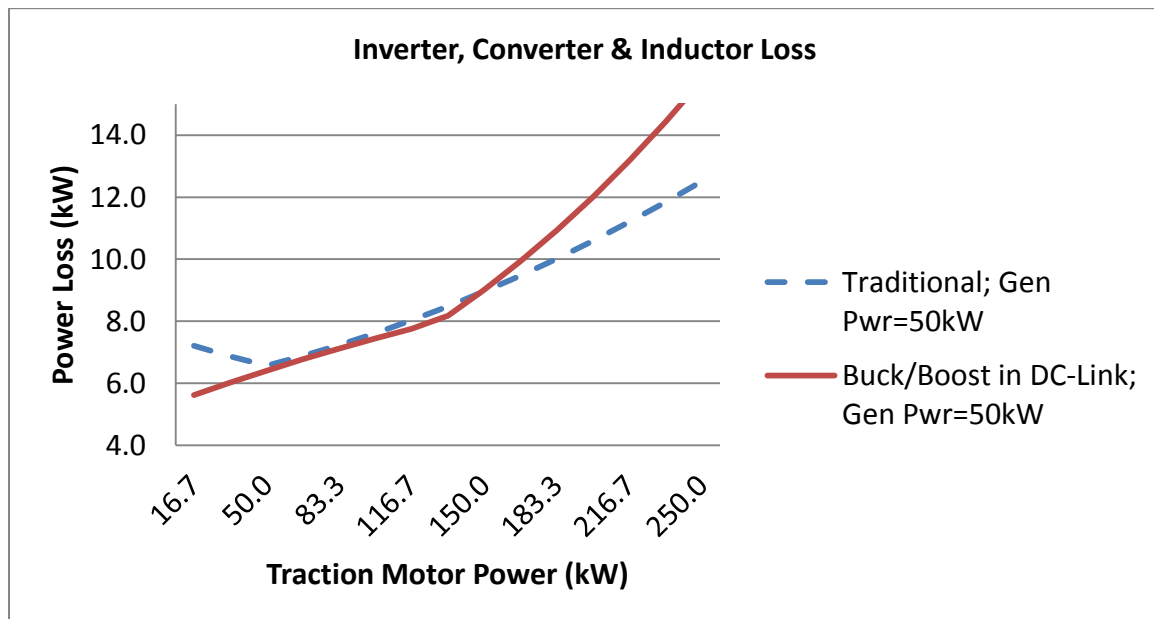


Figure 55 Loss graphs under scenario one conditions (Generator at 50kW) for the Back to back VSI / VSI topology with GI bi-directional buck-boost converter and TI bi-directional buck-boost converter

Since this topology does not provide significant savings, only the 50kW case is displayed.

5.2.5 Back to Back Voltage Fed Quasi-Z-Source Inverters, LV Battery

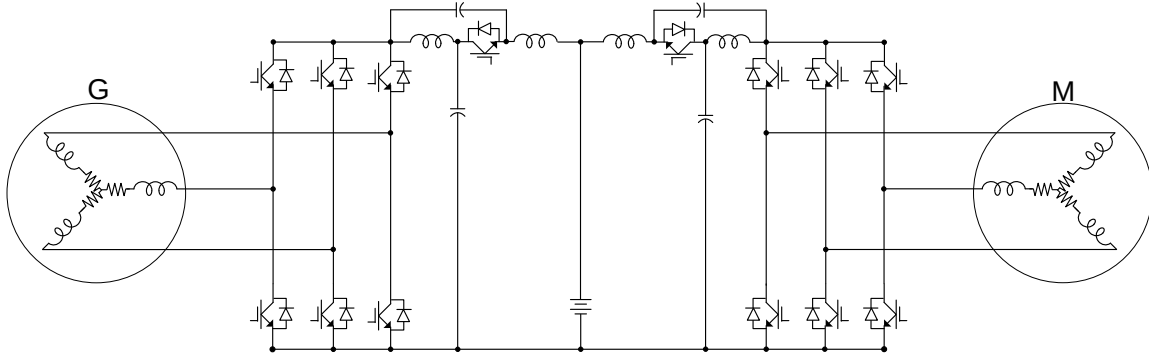
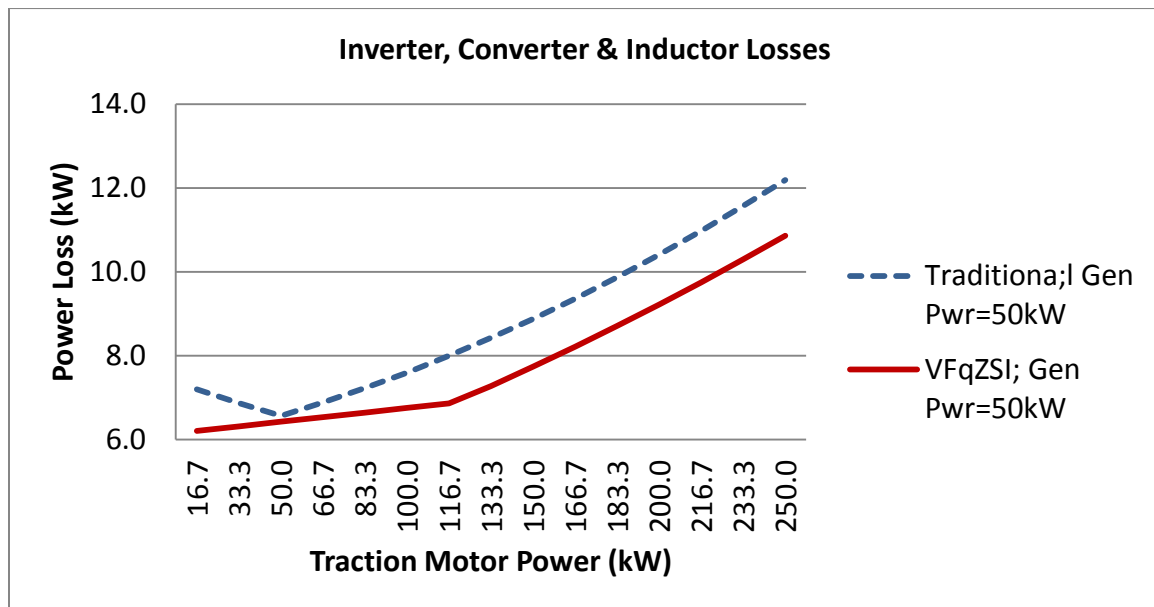


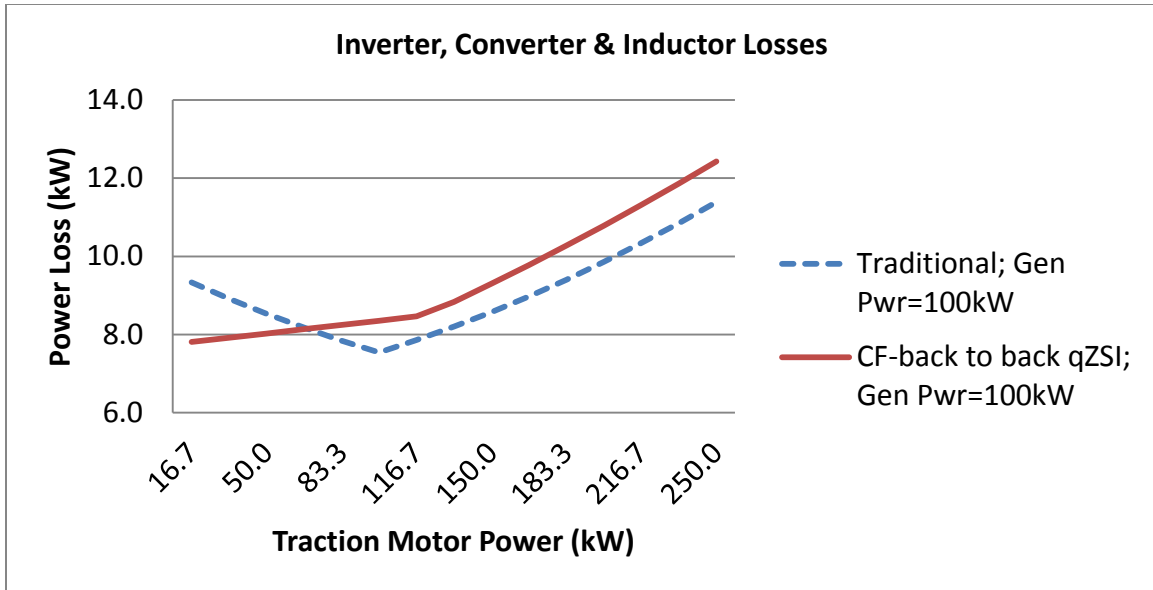
Figure 56 Back to back voltage fed quasi Z source inverter topology.



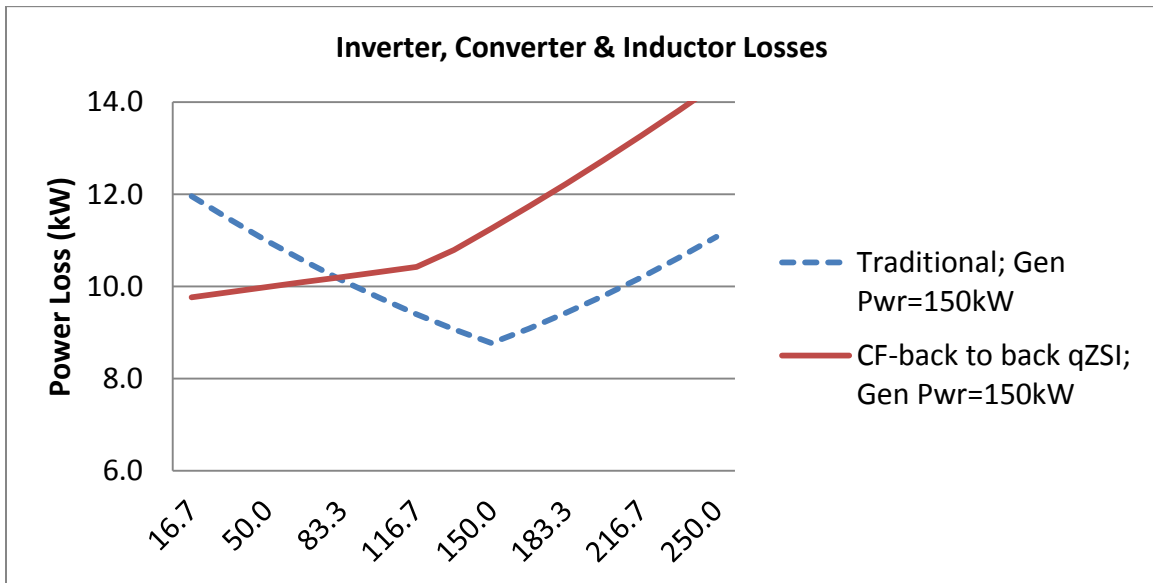
(a) Scenario 1. Generator held at 50kW.

Figure 57 Loss graphs (a, b, and c) for the Back to back voltage fed quasi Z source inverter topology

Figure 57 continued.



(b) Scenario 2. Generator held at 100kW.



(c) Scenario 3. Generator held at 150kW.

5.2.6 Back to Back Current Fed Quasi-Z-Source Inverter, LV Battery

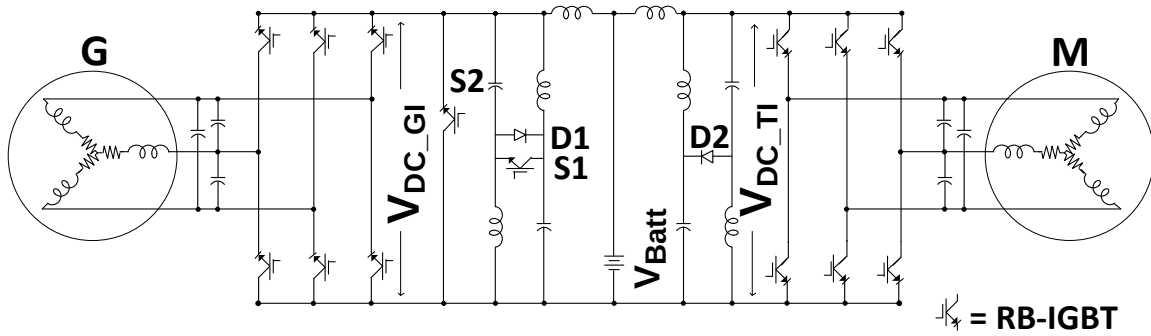
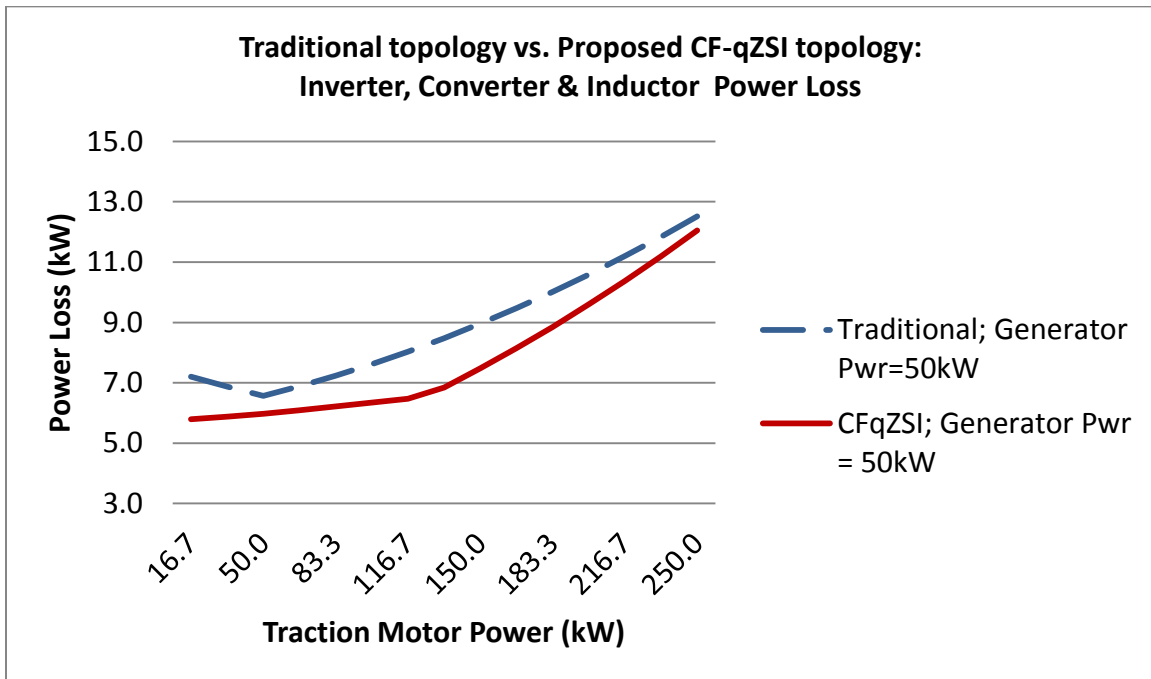


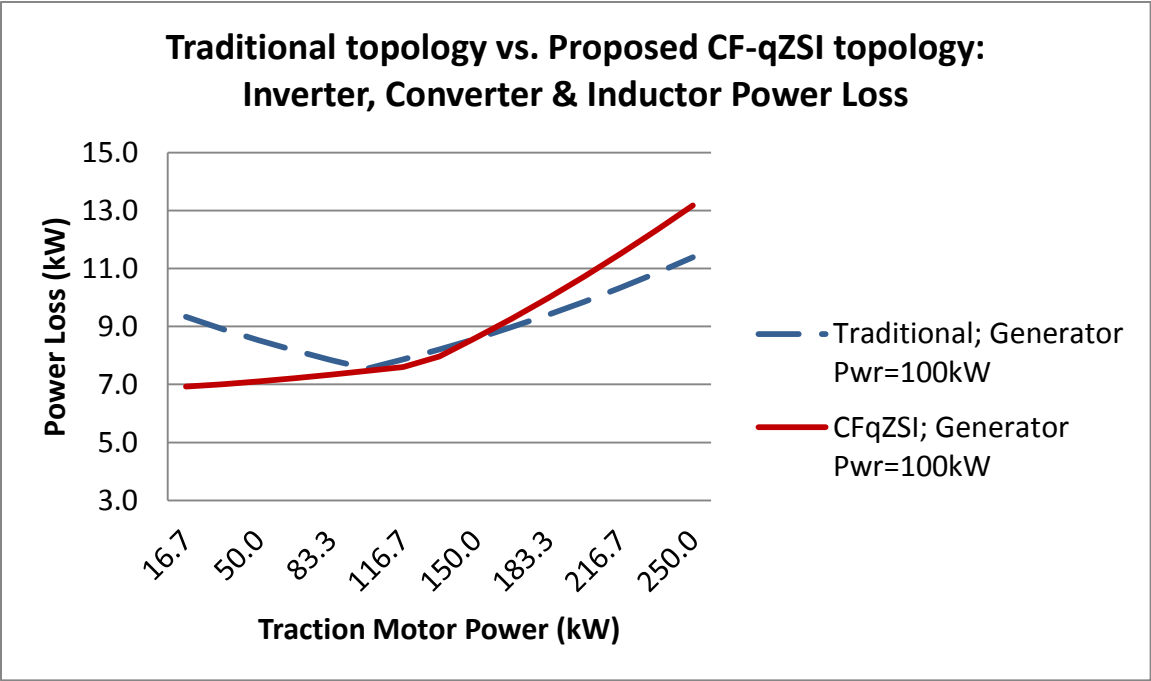
Figure 58 Back to back current fed quasi Z source inverter topology.



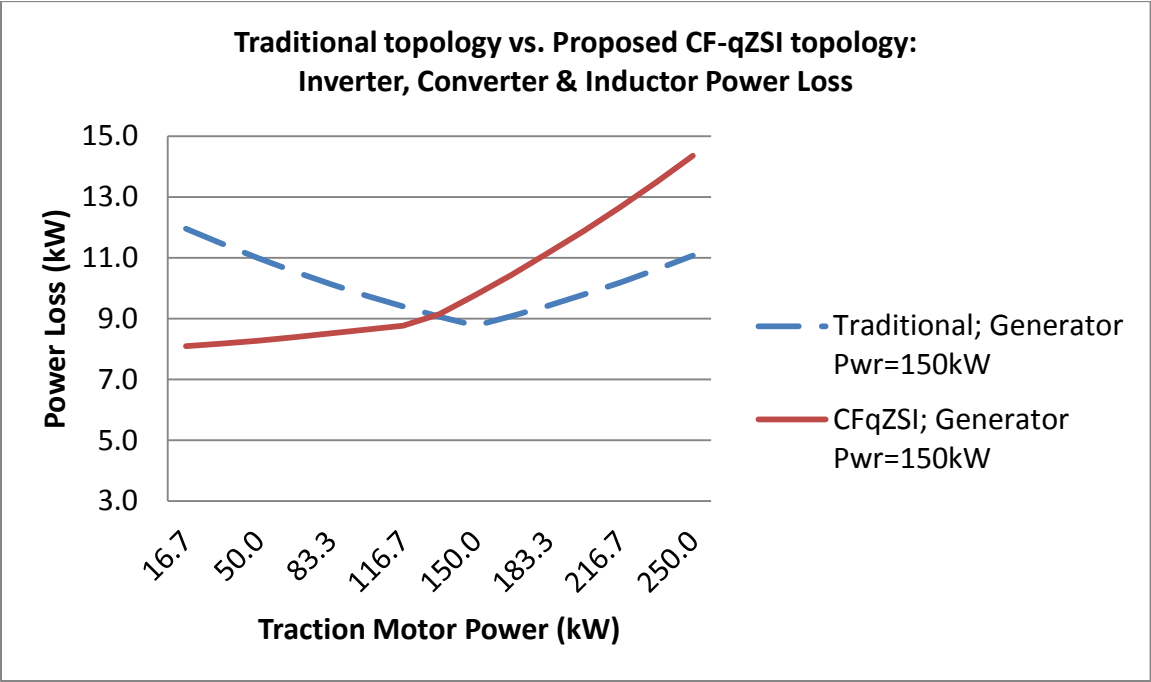
(a) Scenario 1. Generator held at 50kW.

Figure 59. Power loss comparisons between the traditional topology and the proposed CF-qZSI topology under three different scenarios (a), (b), (c).

Figure 59 continued



(b) Scenario 2. Generator held at 100kW.



(c) Scenario 3. Generator held at 150kW.

Although it can be reasoned that the additional components reduce system reliability, the Quasi Z Source Inverter topologies have the added quality that they are not vulnerable to shoot through events which would destroy the switching devices of the traditional VSI topologies [16]. The above topologies are based upon various types of buck, or boost, or buck boost converters implemented in a way that decouples the DC-Link voltage at one end from that at the other. The most promising of these topologies is the back to back current fed qZSI (CF-qZSI) shown in Figure 58. The CF-qZSI will be discussed here in further detail. First it is necessary to discuss the functionality of the CF-qZSI.

Current Fed Quasi “Z” Source Inverter (CF-qZSI):

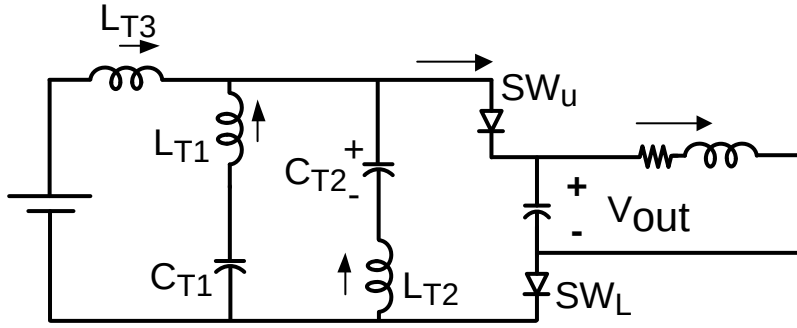
The CF-qZSI uses reverse blocking IGBTs (RB-IGBT) without a free-wheeling diode. This device is able to block voltage in both directions, but can pass current in only one direction. It has slightly higher forward conduction losses, but does not have the free-wheeling diode or the losses that are associated with it. Like the other “Z” source type inverters, the inverter switching devices include an additional zero switching state that is not allowed with the traditional inverters. This additional switching state is frequently referred to as the shoot-through state or short circuit zero state when both the top and bottom switches of a phase leg are closed at the same time. This switching state would destroy the switching devices of the traditional inverter but the switching currents are safely limited in the “Z” source inverters by the inductance of these inverters.

The operation and switching states used to control the circuit configuration at the traction motor end (from the battery to the traction motors) is different than that at the generator

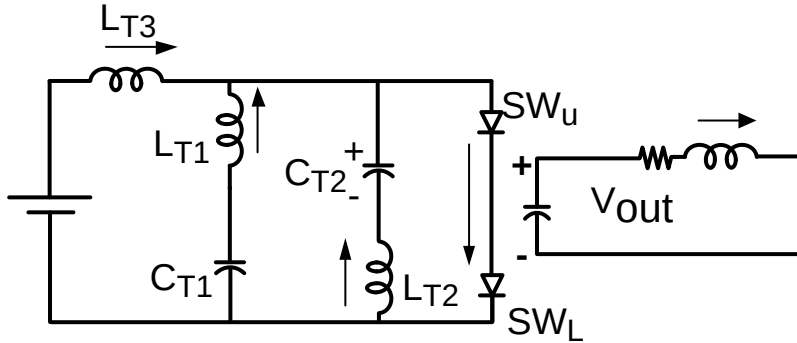
end (from the battery to the generator). Therefore, each will be discussed separately below:

Traction Motor End:

The operation of the traction motor end of the back to back topology is shown in Figure 60. Figure 60 (a), (b), and (c) show the CF-qZSI active, shoot-through (short circuit zero state), and open (open circuit zero) states, respectively. Figure 61 shows the voltage boost or buck results as a function of these states.



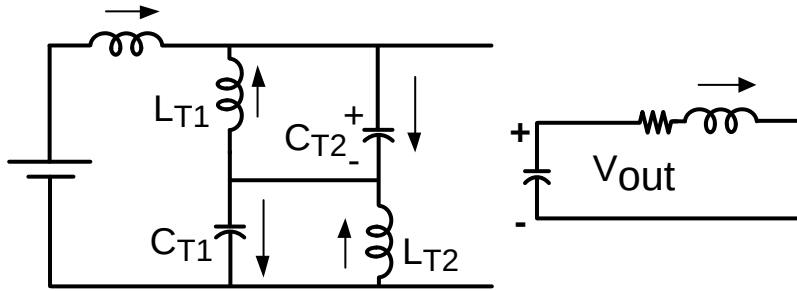
(a) State I– Active State: D_A



(b) State II– Short Zero State: D_{Sh}

Figure 60. Operational states (a, b, and c) of the CF-qZSI [27]

Figure 60 continued



(c) State III– Open Zero State: D_{Op}

When the inverter uses only active states and not zero states, the DC output voltage is equal to the DC input voltage. If boosting this voltage is desired, the active duty cycle will be reduced and short circuit zero states will be added. If bucking is desired, the active duty cycle will be reduced and open circuit zero states will be added. This does not reduce the DC voltage across the TI below the battery voltage, but reduces the voltage seen by the traction motor. In the graph of Figure 61, the red line (upper boundary) is purely active states and short circuit zero states while the blue line (lower boundary) is purely active states and open circuit zero states. Between these two boundary lines, a combination of all three states can be used.

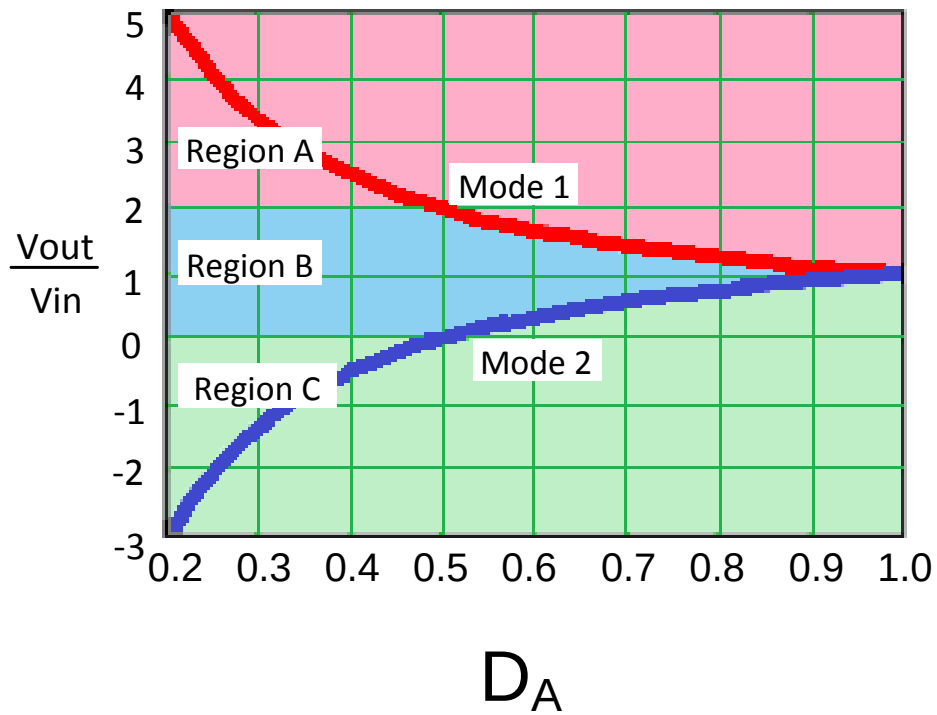


Figure 61. V_{out}/V_{in} vs. active duty cycle. [27]

Mode 1 uses active states and short circuit zero states but not open circuit zero states,

Mode 2 uses active states and open circuit zero states but no short circuit zero states.

At the traction inverter end of the topology, it is this buck and boost capability that allows the energy saving operation of maintaining the DC-Link voltage across the traction inverters to be as low as the battery voltage and as high as is required for full speed operation of the bus.

Generator End:

The operation of the qZSI configuration at the generator end of the topology is a bit different. The qZSI at this end is used to buck the generator voltage down to the level of the battery by using the active and open circuit zero states.

$$\frac{V_{batt}}{V_{DC-GI}} = D_A \quad (\text{eq 5.20})$$

Where:

D_A is the active duty cycle of the generator inverter switches,

V_{batt} is the battery voltage, and

V_{DC-GI} is the DC-Link voltage across the generator inverter.

In this case, as the active duty cycle is reduced from 100%, it is the open circuit zero state that is increased and the short circuit zero state is not used while pushing power from the generator to the battery and traction inverter. Figure 62 shows the generator end of the topology.

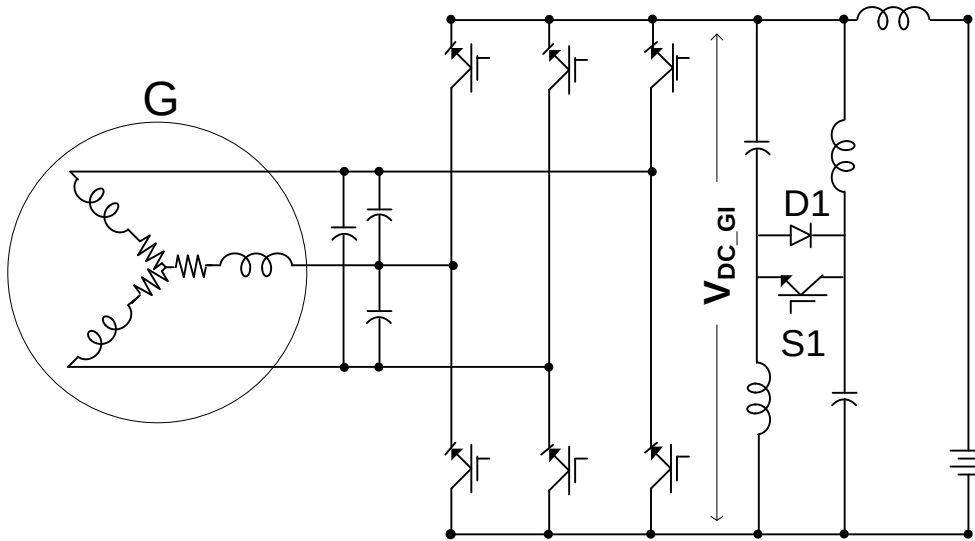
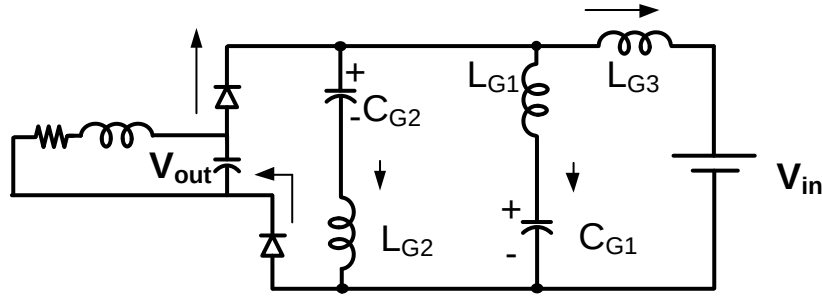


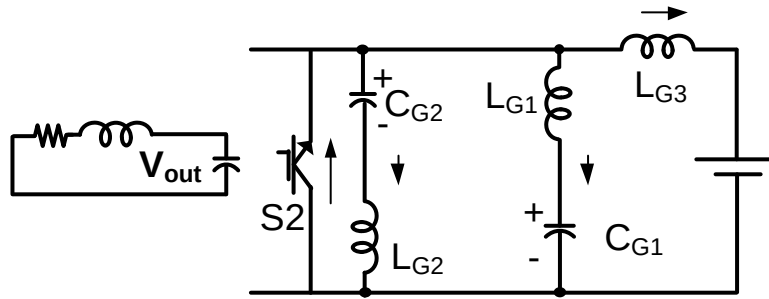
Figure 62. Generator end of the back to back CF-qZSI topology

This end of the topology is not a complete mirror image of that at the traction motor end. The RB-IGBTs are flipped over allowing the top DC-Link rail to be polarized with a positive voltage from the generator and an additional IGBT has been added in the middle of the “Z” source impedance network. This switch “S1” remains open during normal operation and is only closed when power is to be pushed from the battery to the generator to start the diesel engine. Also, there is an additional switch S2 which is gated on at all times except when the ICE is being started. When gated on, it functions like a diode and conducts in the state shown in Figure 63.

While the generator is running and power is being pushed from the generator to the battery and the TI, the generator’s voltage level must be bucked. To accomplish this, the following switching states are used.



(a) GI active state with power being pushed to the battery and TI. S1 and S2 are open

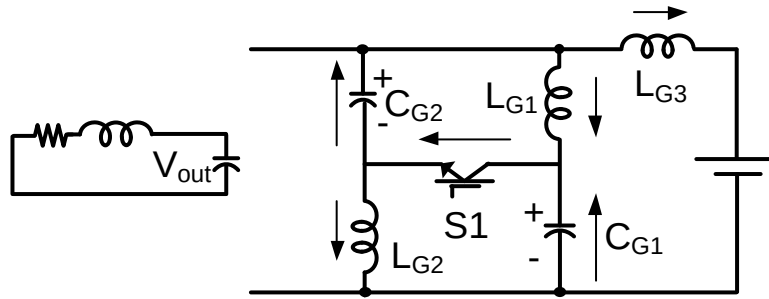


(b) GI open circuit zero state with S2 conducting. S2 is closed, S1 is open.

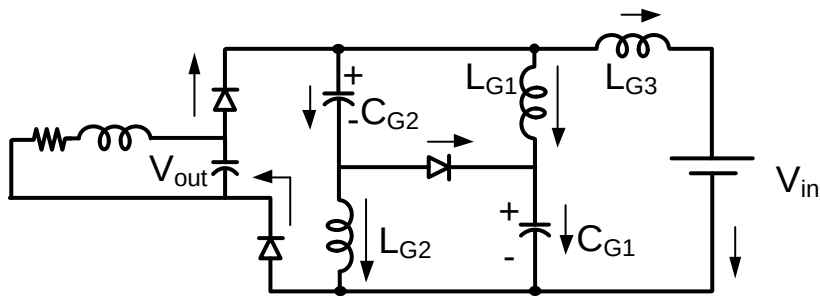
Figure 63. (a) and (b) GI voltage is being bucked from the GI level down to the battery level.

During state 1 shown in Figure 63 (a), generator voltage is imposed across inductor L_{G3} and the battery. Inductor L_{G3} provides a voltage drop and the battery only sees a voltage lower the V_{DC_GI} . The duty cycle of this state is controlled to maintain the correct voltage across the battery. Following this state, the state of Figure 63 (b) is entered. During this state, switch S2 turns on and allows the currents in the inductors to decay. Below in Figure 64, the switching states used to start the diesel ICE are displayed. Since the GI uses RB-IGBTs, power cannot be pushed toward the generator by simply

reversing the flow of current as can be done with the more common VSI. In this case, voltage polarity must be reversed to reverse power flow. Figure 64 (a) shows the initial state. In this state, S1 is closed which impresses the voltage of C_{G2} across L_{G1} , and C_{G1} across L_{G2} . The voltage across each capacitor is equal to the battery voltage. This energizes these inductors in preparation for the next state. In Figure 64 (b), S1 opens and the GI enters its active state. This pushes power to the generator and the GI now functions to drive the generator as a starter motor.



(a) Open circuit zero state with S1 closed and S2 open.



(b) Active state with S1 and S2 open.

Figure 64. The switching states used to start the diesel ICE

Calculation of Losses for the proposed back to back CF-qZSI topology:

The power losses for the CF-qZSI were calculated in a manner similar to that used for the traditional hybrid bus of figure 3. However, there are several differences that must be taken into account. The CF-qZSI uses reverse blocking IGBTs (RB-IGBT) instead of the common IGBT module with the anti-parallel, free-wheeling diode. The RB-IGBT has slightly higher forward conduction losses, but does not have the losses from an anti-parallel free-wheeling diode. The qZSI impedance network on the generator inverter side includes an IGBT module (IGBT and its anti-parallel diode) which does not exist in the traditional hybrid topology and the switching, conduction, and reverse recovery losses of this device have to be considered for the modes under which they turn on, off or conduct accordingly. You will also notice the two inductors of this impedance network and an inductor connected to the battery node. The losses of these inductors have also been estimated in the same manner as that of eq. 5.13 based upon the power flow through them and the core losses (hysteresis and eddy) associated with the changing magnetic field (ΔB) which results from boost or buck functions. Also, the capacitors of the qZSI impedance network are equivalent to those of the traditional topology and the comparative losses were found to be inconsequential and therefore, the capacitor losses of both the traditional and proposed topologies are ignored in this study.

The inductor losses on the inductor on the TM side of the battery node and of the impedance network for the TM qZSI are likewise calculated as well as the conduction and reverse recovery losses of the diode in that impedance network. Also, the Traction inverter has an additional switching state that the traditional VSI does not have [16] [27].

This shoot-through state in which both the top and bottom switching devices of a phase leg are gated on at the same time, provides an important function of this unique type of inverter that allows it to boost the voltage seen at the input to the traction inverter, and the losses of this additional switching state (turn on, turn off, and conduction) are also included in the analysis.

The Z-source topology does not require the dc/dc converter and therefore avoids the switching and conduction losses associated with that; however, it does utilize an extra switching state for shoot-through. This state occurs during the open circuit zero state during which all 6 RB-IGBTs are open. The OCZ state of the CF-qZSI is different than that of the voltage fed type of inverters where all 3 upper IGBTs are closed or all 3 lower IGBTs are closed to create this state. When the TI of the CF-qZSI enters the SCZ state, it closes the upper and lower switches of one phase leg leaving the other four RB-IGBTs open. Since the RB-IGBTs conducting the SCZ current had been open, and will return to of the open state, these two switches incur a turn on, turn off, and conduction loss associated with this SCZ state. This also is included in the analysis, and the following power loss equations are added to the Z-source topology.

$$P_{ON_ST} = \frac{V_{cc} M t_{rN} I_{cM}^2 F_s \cos(\theta)}{2\pi I_{cN}} \quad (\text{eq 5.21})$$

$$P_{i_ST} = \left(\left(\frac{V_{ceN} - V_{c0}}{I_{cN}} \right) \left(\frac{1}{2} M I_{cM} \cos(\theta) \right) + V_{c0} \right) *$$

$$\left(\frac{1}{2}MI_{cM} \cos(\theta)\right)\frac{T}{2}\left(1-\frac{M}{B}\right)F_s \quad (\text{eq 5.22})$$

$$P_{off_ST} = \left(\frac{V_{cc}MI_{cM}t_{fN}F_s \cos(\theta)}{6}\right)\left(1 + \frac{MI_{cM} \cos(\theta)}{4I_{cN}}\right) \quad (\text{eq 5.23})$$

Where the variables are as defined at eq 5.4.

To summarize the loss effects of the traditional hybrid vs. the proposed back to back CF-qZSI:

- The proposed topology has additional losses that result from additional components and switching states:
 - “Z” source impedance network inductors and Inductors connected to the battery node
 - Reverse blocking feature of the inverter switching devices
 - Additional IGBT module included in the generator end “Z” source network
 - Additional diode included in the traction motor end “Z” source impedance network, and
 - Additional switching states of the “Z” source type inverters.
- The proposed topology has lower losses that result from:
 - not having a separate DC/DC converter connected to the battery, and
 - The new ability to decouple the DC-Link voltage present at opposite ends of the topology.

All of the positive and negative loss effects of both the traditional hybrid topology and the proposed topology were then aggregated for comparison as shown in Figure 59.

5.3 Conclusion

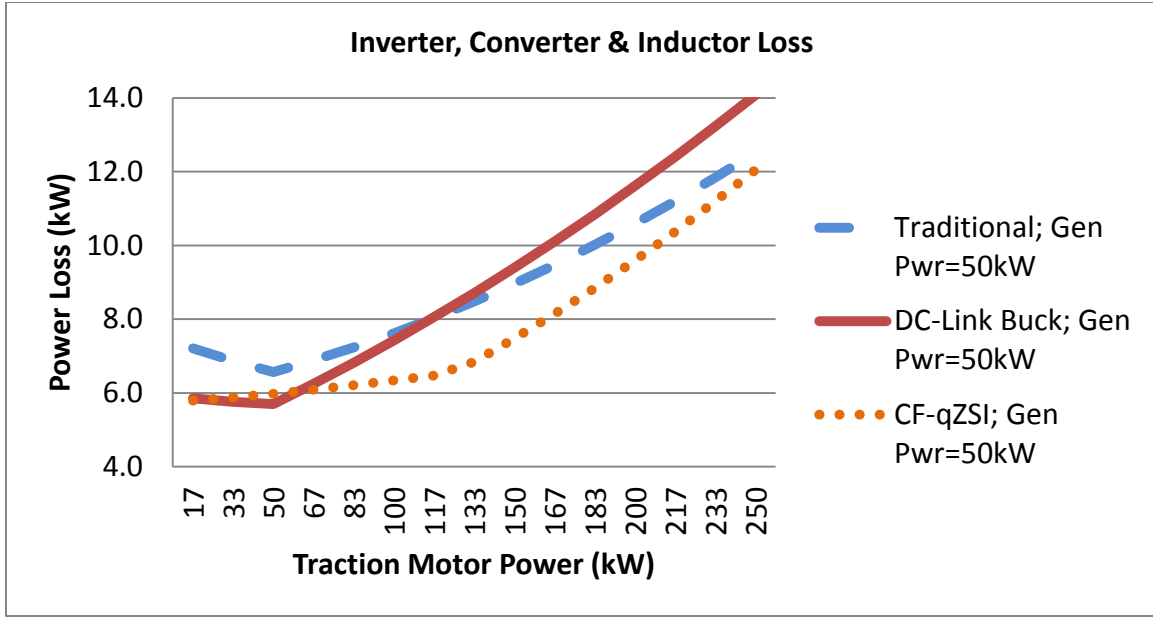
Several topologies were devised analyzed and presented with the purpose of seeking a topology that would allow each major component of the hybrid bus to operate within its most efficient region. Three topologies in particular do show significant decreases in losses for lower speed operation of the bus which is its most common range of speeds.

These new more efficient topologies are the:

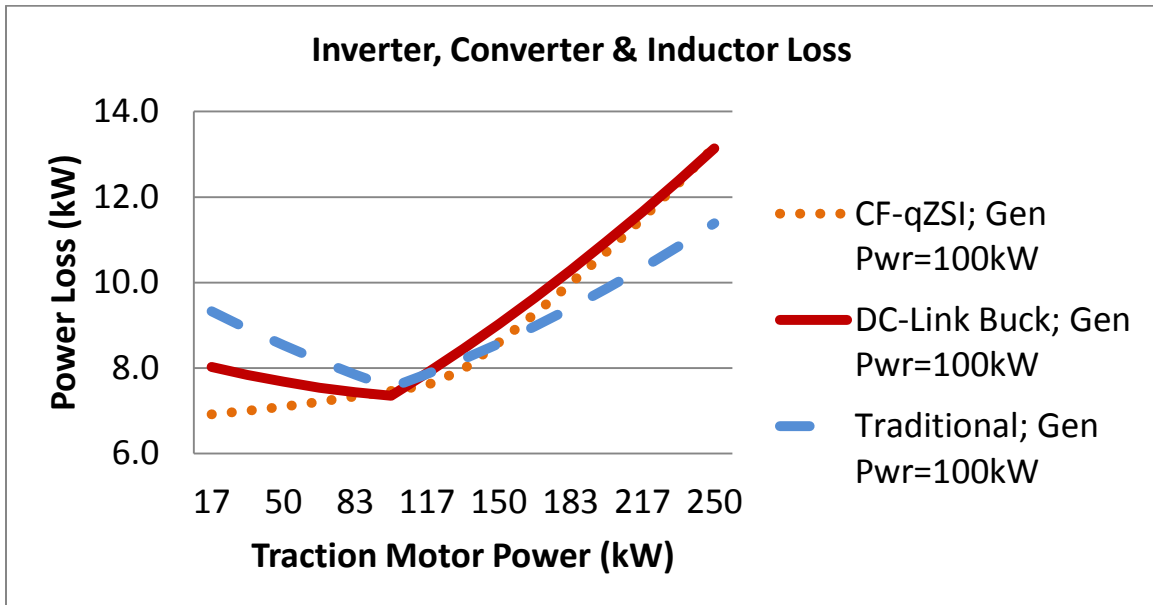
- (1) VSI / VSI Structure with a LV Battery and Boost Converter, & a DC-Link with a Buck Converter;
- (2) Back to Back Voltage Fed Quasi-Z-Source Inverters with a LV Battery; and
- (3) Back to Back Current Fed Quasi-Z-Source Inverters with a LV Battery.

The commuter bus optimized with one of these new topologies would be an ideal candidate for implementation as a parallel or series parallel hybrid. In such an implementation, the additional high power operation could be accommodated via the parallel mechanical power flow path. This would allow the power electronics to always remain within the more efficient power and speed ranges. In effect, this would utilize the electric components to function in the regions where they provide more efficiency than the traditional hybrid vehicle and allow a mechanical power flow path to deliver just the high power in the regions of operation where it is the most efficient.

Of these three advanced topologies, the “VSI / VSI Structure with a LV Battery and Boost Converter, & DC-Link with a Buck Converter” (Here after referred to as “VSI/VSI with DC-Link Buck”) topology and the “Back to Back Current Fed Quasi-Z-Source Inverters with a LV Battery” (hereafter referred to as “Back to Back CF-qZSI”) provide the most energy savings. The VSI/VSI with DC-Link Buck is the most simple and yet provides significant energy savings. The Back to Back CF-qZSI offers the lowest energy loss in a wider range of operating regions. Below in Figure 65 are comparative graphs for these two topologies and the traditional topology. Figure 65 (a) shows the traction motor power sweep while the generator power is held at 50kW (scenario 1). Figure 65 (b) shows the same traction motor power sweep while the generator is held at 100kW (scenario 2), and Figure 65 (c) shows the same sweep while the generator is held at 150kW (scenario 3).



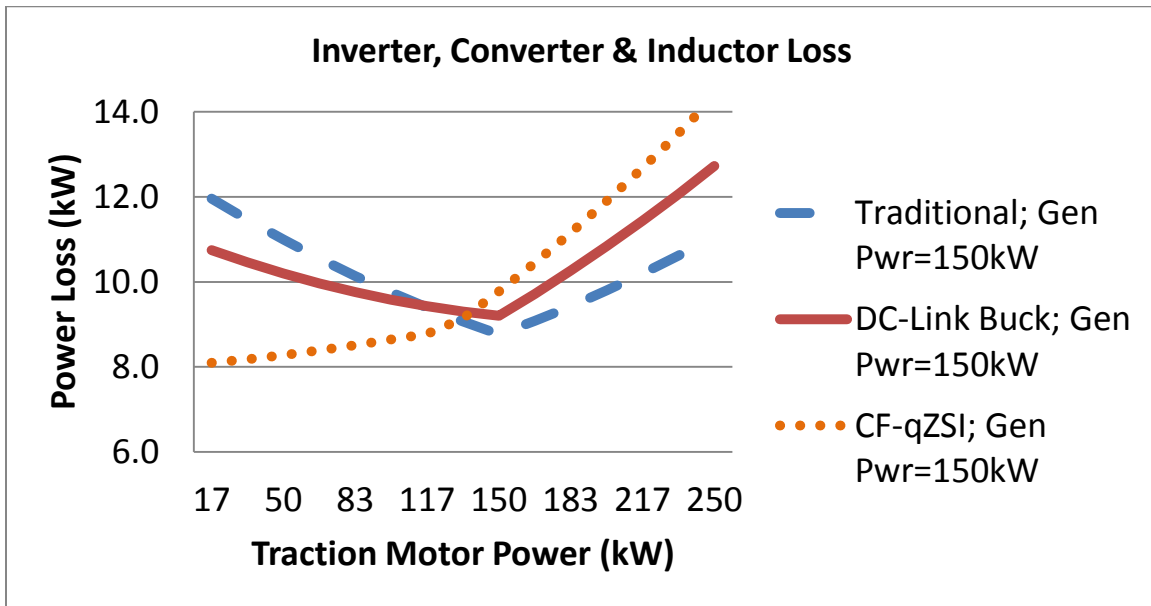
(a) traction motor power sweep while the generator power is held at 50kW (scenario 1)



(b) traction motor power sweep while the generator power is held at 100kW (scenario 2)

Figure 65 Comparative power loss graphs for the Traditional, Buck Converter in DC-Link, and CF-qZSI topologies for three different operating scenarios (a), (b), and (c).

Figure 65 continued



(c) traction motor power sweep while the generator power is held at 150kW (scenario 3)

As shown in the graphs above, the new topologies offer significant savings of energy at important operating points. A summary of the pros and cons of the VSI/VSI with DC-Link Buck and the Back to Back CF-qZSI is presented just below.

VSI/VSI with DC-Link Buck:

Pros:

- **decreased losses for traction motor power below 117kW.**

Cons:

- **an additional inductor.**
- **two additional IGBT modules.**

Back to back CF-qZSI:

Pros:

- **lowest losses at low vehicle speed.**
- **lowest losses over a wide speed range for scenario 1.**
- **system is protected against shoot through events.**
- **freewheeling diode count is very low.**

Cons:

- **additional inductors.**
- **two additional IGBT modules.**

As a result of this work, a new full system analysis has been done, and based upon this analysis, a new generator inverter to traction inverter voltage decoupled structure has been proposed. The voltage decoupling method has been proven via experimental

results, and the analytical method implemented in this work has been verified via experimental results. Several new voltage decoupling topologies have been developed and analyzed. The analysis method has been used to choose the two best topologies (VSI/VSI with DC-Link Buck, and Back to Back CF-qZSI) which have been compared to each other and to the existing traditional topology. Significantly improved efficiencies have been achieved by this research and the new topologies proposed as its result.

6. Future Work

Future work recommend is to devise a by-pass method that allows the lower high speed power losses of the traditional topology as well as the lower low speed power losses of the new topologies. A type of parallel hybrid or series parallel hybrid could be a good candidate for this. Also, a type of electrical bypass solution should be sought that allows the voltage decoupling systems to be by-passed when they are not needed.

As a result of the voltage decoupling concept, the traction inverters are allowed to operate at a modulation index of one and it is known that this reduces the harmonic content seen by the traction motors thereby improving their efficiency as well. The extent to which this occurs should be quantified.

The Back to Back CF-qZSI topology has the capability to boost the DC-Link voltage. As a result, the traction motors could be kept below the field weakening region for a longer period of time by increasing the output voltage of the inverters as the field weakening region is approached. This allows the additional current required to weaken the rotor field to be avoided and thereby reduce losses of the traction motors. This should also be quantified.

Thirdly, the new topologies allow the speed of the diesel engine and therefore the speed and voltage of the generator to be held in a narrower range. As a result, the efficiency of operation of the engine and of the generator could be optimized for this operating point and result in greater energy savings which should also be quantified.

The power electronics energy savings of the new topologies have been investigated in this work, but there are additional savings that result from the whole system approach used here. As suggested in the previous three paragraphs, the new topologies provide additional savings opportunities in the diesel engine, generator, and traction motors that have not yet been quantified. This future work will show that the new topologies are even more beneficial than documented here.

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