# Design of Z-Source Inverter for Electric Bikes



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## **Design of Z-Source Inverter for Electric Bikes**

by Wencong Zhang

## **Research Project**

Submitted to the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, in partial satisfaction of the requirements for the degree of **Master of Science, Plan II**.

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## Abstract

This technical report presents the design of a Z-source inverter for an electric bike controller. The objective of this work is to evaluate the potential of using this non-standard inverter topology for a medium power (250W - 3kW) motor drive application. The Z-source inverter is able to use the shoot-through state to boost the dc bus voltage, which enables a permanent magnet motor to achieve a higher top speed. In addition to a concise review of relevant work done on this topic, this report also presents an original analysis on the switching behavior of the Z-source inverter and proposes the *minimum switching space vector modulation* control strategy. The design of a 1.5kW Z-source inverter prototype is detailed and the advantages of the proposed control strategy are verified experimentally.

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## Introduction

Power inverters are a class of circuits that convert DC power to AC power and they are the fundamental building block of any electric variable speed drives. With the growing electrification of transport, there is a need to design inverters suitable for a range of drive applications. This report focuses on the inverter design for a low to medium power (250W -3kW) drive application such as an electric bicycle or an electric moped.

Any battery-powered electric drive system consists of three basic building blocks: batteries, power inverters and electric machines. In the case of an electric bike, sealed lead-acid (SLA) batteries or Li-ion batteries (Fig.1) are the most commonly used. Asia accounts for 90% of the global market for electric bikes and most e-bikes sold in Asia use SLA batteries due to their relatively lower cost. A typical battery arrangement is to put three to six 12V SLA battery packs in series to provide 36 to 72V source voltage. Li-ion batteries are used on highperformance e-bikes for their much superior energy density. Typically, 18650 Li-ion cells with nominal voltage 3.7V are configured in a series-parallel connection to provide the desired voltage and maximum current output capability; the pack voltage is commonly configured to be from 24V to 72V.



Figure 1(a): 12V SLA Battery



Figure 1(b): E-bike Li-ion Battery Pack

The electric machines employed in these electric drive systems are almost exclusively surface permanent magnet synchronous machines (SPM) because of their simplicity and high torque density (Fig. 2a). Gears may be used in motors with small form factors to trade speed for torque (Fig. 2b). The torque output of a SPM is proportional to its current and its back-EMF is proportional to its speed. Therefore, if a voltage source inverter is used, which can only step down the input voltage, the voltage of the battery pack determines the top speed or no-load speed of a SPM. In addition, as the motor approaches its top speed, its torque and power output drop sharply because the battery pack does not have enough voltage to push high current into the fastspinning motor. For induction machines that are sometimes used on electric vehicles (EVs), field weakening can be used to extend the speed of the machine beyond its base speed. This is achieved by reducing its magnetizing current hence the air gap flux. This technique is inefficient and even impractical with SPMs because the windings in an SPM typically have low inductance, which means that it would require a significant amount of current to counteract the magnetic field provided by the permanent magnets. The heat generated from this large amount of current not only reduces the efficiency of the drive, but also runs the risk of overheating under continuous operation.





Figure 2(b): Planetary Gears in an E-bike Hub Motor

Figure 2(a): E-bike SPM

To increase the top speed of an SPM, the most direct approach is to have an inverter that is able to boost the battery voltage. A boost converter front-end is well suited for this purpose although the costs of extra circuitry and control complexity have prohibited the commercialization of such two-staged approach for low to medium power drive systems (Fig. 3). A novel single-stage topology that has received a lot of attention recently is the Z-source inverter, which utilizes the traditionally forbidden shoot-through states to boost the voltage. (Fig. 4) [1]. Having the voltage boost functionality in an inverter does not only allow the motor to go faster, but also allows the motor to maintain constant speed under battery voltage fluctuations.



Figure 3: 2-Stage Boosted Inverter Topology



The concept of a Z-source inverter was first proposed in 2002 by Prof. F.Z.Peng [1]. Since then, Z-source-related research has grown rapidly: an array of Z-source inverter topologies and control strategies has been proposed to improve on the original concept. This report discusses the design of a 1.5kW Z-source inverter for an e-bike application and presents a new control strategy that reduces switching loss and the average stresses on the switching devices and passives compared to the popular *constant boost control* [2].

### **Z-Source Inverter Overview**

#### **Topology and Principles of Operation**

The Z-source inverter topology, shown in Fig.4, has a unique impedance network frontend consisting of two inductors and two capacitors. Compared to a voltage-source inverter that can only operate in 6 actives states and 2 zero states, the Z-source inverter can also operate in the shoot-through states where the upper and lower switches in one or more phase legs are gated on simultaneously. Since shoot-through events no longer result in inverter failures, the Z-source inverter is more robust against EMI and parasitic turn-on of devices. Illustrated in Fig.5 are the equivalent circuits of the shoot-through states and non shoot-through states of the Z-source inverter.



Figure 5(a): ZSI in Shoot-through State



In the following description of the circuit operation, we assume that the capacitors in the impedance network ( $C_1$  and  $C_2$ ) are identical. We also make this assumption for the inductors  $L_1$  and  $L_2$ . Then, based on the symmetry of the circuit, capacitor voltages and inductor currents are typically observed to be the same in practice. The capacitors in the impedance network ( $C_1$  and  $C_2$ ) are initially charged to the input voltage  $V_{in}$ . During the shoot-through state, the source diode  $D_1$  is reverse biased and it blocks a voltage  $2V_{cap} - V_{in}$ . Therefore, the input is disconnected from the rest of the circuit. Due to the short circuit in one or more phase legs, the voltage across each inductor in the impedance network ( $L_1$  and  $L_2$ ) is  $V_{cap}$ ; energy is transferred from  $C_1$  to  $L_1$  and  $C_2$  to  $L_2$ . In the non shoot-through state, the diode  $D_1$  is forward biased and the inverter bus voltage is  $2V_{cap} - V_{in}$ ; energy is transferred from  $L_1$  to  $C_2$  and  $L_2$  to  $C_1$ .

The detailed derivation of the steady state voltages has been presented in [1] and this report presents some key equations relevant to inverter operation and control design. In the following equations, *d* represents the shoot-through duty cycle, *M* is the modulation depth of the inverter, *B* is the boost factor from input voltage to inverter bus voltage, <> means taking the periodic average of the value inside the bracket, V<sub>AC</sub> is the output peak AC voltage without using overmodulation and V<sub>bus nst</sub> is the V<sub>bus</sub> voltage during non shoot-through state.

$$V_{cap} = \frac{1-d}{1-2d} V_{in} \tag{1}$$

$$V_{bus\_nst} = \frac{1}{1-2d} V_{in} \tag{2}$$

$$\langle I_L \rangle = \langle I_{in} \rangle \tag{3}$$

$$V_{AC} = M \times B \times \frac{V_{in}}{2} \tag{4}$$

It is worth mentioning that there are variant Z-source topologies based on the original Zsource topology presented above. The two most notable variant topologies are the quasi Z-source inverter and the trans Z-source inverter (Fig. 6). The quasi Z-source inverter has the advantage of continuous input current and easier layout design [3]. The trans Z-source inverter uses coupled magnetics to achieve higher voltage gain [3].



Figure 6(a): Quasi ZSI

Figure 6(b): Trans ZSI

#### **Z-source Inverter Modulation Strategies**

Reference [4] presents a comprehensive review of different Z-source inverter modulation strategies. This report focuses on the modulation techniques for three phase (2 Level) Z-source inverters because they are commonly used in motor drive applications. These proposed strategies could be broadly categorized as sine PWM (SPWM) and space vector PWM (SVPWM). These strategies aim to achieve a wide range of modulation, less commutation per switching cycle, lower device stress and smaller size requirements for passives. *Simple control* [1], *maximum boost control* [5] and *maximum constant boost control* [2] are widely cited SPWM control strategies. Since space-vector modulation is a more natural choice for motor drive applications with the advantage of generating higher voltages with lower THD, this report discusses and compares the SVPWM ideas. In succinct terms, *simple control* and *constant boost control* use constant modulation depth and constant boost factor. *Maximum boost control* uses constant modulation depth and time-varying boost factor.

Unlike a 2-stage boosted inverter topology where the voltage boost is independent of the modulation depth of the inverter, the Z-source inverter has a fundamental trade-off between shoot-through states and active states. Therefore, the Z-source inverter is intrinsically inferior in terms of bus utilization. Simple control presented in [1] has the advantage of implementation simplicity but does not utilize the inverter bus voltage efficiently. Therefore, the device voltage stress is high, as an unnecessarily large boost is required to achieve a certain AC output. *Maximum boost control*, presented in [2], has the most efficient bus utilization since it converts all traditional zero states into shoot-through states. However, due to the non-constant shoot-through duty cycle, large passives are required to suppress the low frequency (6 times the output frequency) voltage ripple on the inverter bus. *Maximum constant boost control* with 3rd harmonic injection proposed in [3] achieves constant shoot-through duty cycle by not converting all potential zero states. Shown in Fig.7 is the shoot-through duty cycle comparison in an output period between the two schemes.



Figure 7: Shoot-through Duty Cycle Comparison

The two schemes can also be visualized on a space vector diagram. Shown in Fig.8a is the *maximum boost control*. The yellow region represents the time allocated to traditional zero states that can be converted to shoot-through states. If a constant modulation depth is used, there is more time for shoot-through states near the vertices of the hexagon. In Fig.8b, the yellow region representing the shoot-through states has pulled back from the vertices and the green region represents the unconverted zero states. Under this modulation, the size requirement of the passives is significantly reduced but it incurs higher voltage stress on the devices compared to *maximum boost control*.



Figure 8(a): Maximum Boost Control

Figure 8(b): Maximum Constant Boost Control

Since the shoot-through states can be accessed in the Z-source inverter, the set of possible gating patterns is larger than that of a voltage source inverter. This freedom to access the shoot-through states gives rise to new opportunities in designing innovative modulation strategies. The design of switching patterns is guided by the tradeoff between the size of the passives and switching loss. In order to minimize the size requirement of the passives in the impedance network, we want to insert as many shoot through states as possible. However, to keep switching loss low, we must also minimize the frequency of switching actions. Fig. 9 shows a symmetric space vector switching pattern where 6 shoot-through events are distributed in a switching more switching events than the traditional symmetric space vector modulation. If we convert all the zero states, both (000) and (111), into shoot-through states, then two gate signals (A+ and C- in the example) will be held high throughout the switching period, thus reducing the switching loss by 1/3 in the converter. This control strategy will be explained in detail in section 4.3.



Figure 9: Modified Symmetric SVM for ZSI

#### **Z-Source Inverter Switching Analysis**

The unique topology of the Z-source inverters (ZSI) has attracted much attention from researchers but the relatively more difficult layout of the ZSI has prohibited its adoption in industry [3]. For example, significant voltage spikes during switching is a known issue in ZSI. Regrettably, the analysis of the switching dynamics in ZSI has been largely ignored in literature. This section aims to provide an original analysis of the switching behaviors of ZSI and recommend layout and control guidelines to mitigate voltage spikes in ZSI design.

In order to remedy the voltage spikes, the current commutation during switching and the critical parasitic inductance need to be identified. The analysis of voltage source inverter commutation is reviewed and extended to the ZSI.

Shown in Fig.10a is a single-phase voltage source inverter. The output is modeled as a constant current source with amplitude  $I_{out}$ . The yellow loop is where the commutation current flows and where the parasitic inductance causes ringing at the switching node. The magnitude of the ringing depends on the parasitic inductance, the magnitude of the commutation current and the device output capacitance, assuming the gate turn-on/turn-off time has been fixed. In this case, the magnitude of the commutation current is equal to the absolute value of the output current; the direction of the output current does not affect the magnitude of the ringing.





Figure 10(a): High Frequency Loop in Voltage Source Inverter

Figure 10(b): High Frequency Loop in ZSI

A single-phase ZSI is redrawn in Fig. 10b. The inductors in the impedance network are assumed to be large so that current sources of magnitude IL are used to replace them. When the upper and lower switches are operated without shoot-through, the diode is on. Comparing Fig.9b with Fig.9a, it is obvious that the commutation current loop is the shaded yellow region and the magnitude of commutation current is again equal to the absolute value of the output current. The analysis for state transitions involving the shoot-through state is subtler. We first assume that the lower switch is on and the upper switch is turned on and off to enter and exit the shoot-through state. This is shown in Fig.11a. When the top switch is off, the current flowing in it is 0. When the switch is gated on, the diode is turned off and the current flowing is 2I<sub>L</sub>. The commutation current loop is still the yellow region but the magnitude of the current is 2IL. Next we consider the case where the upper switch is on and the lower switch is turned on and off to enter and exit the shoot-through state. This is shown in Fig.11b. When the lower switch is gated on, the current flowing through it jumps from 0 to 2I<sub>L</sub> - I<sub>out</sub>. Therefore, the commutation current loop is still the yellow region but the magnitude of the current is 2I<sub>L</sub> - I<sub>out.</sub> It is interesting to note that the direction of the output current matters here; the worst-case commutation current has a magnitude of  $2I_L + |I_{out}|$  when  $I_{out}$  flows into the switching node.





Figure 11(a): Shoot-through via Upper Switch

Figure 11(b): Shoot-through via Lower Switch

We can extend this analysis to a three-phase ZSI, which is shown in Fig.12. The currents flowing in the inverter link marked in red are 0,  $I_{out}$  and  $2I_L$  in zero, active and shoot-through states respectively. The worst-case commutation current depends on the direction of  $I_{out}$ . Under the assumption of unity power factor,  $I_{out}$  is non-negative. As power factor decreases, worst-case  $I_{out}$  also becomes more negative, resulting in higher commutation current.



Figure 12: High Frequency Loop in ZSI

#### **Impedance Network Passives Requirement Analysis**

One drawback of the Z-source inverter topology is the requirement of bulky passives L1, L2,  $C_{in}$ ,  $C_1$  and  $C_2$  [3]. Metrics such as energy stored or RMS volt-ampere ratings can be used to evaluate the size and loss of the passive components in power electronics. In this report, the differential power concept introduced in [6][8][9] is adopted because it is a very general concept that examines how efficaciously power is transferred from the input to the output. The differential power of a passive component is the energy processed by that component in one switching cycle.

The differential power analysis of the ZSI can be found in Appendix 1. For comparison, the same analysis is performed on an inverter with a boost converter front-end (boosted inverter). The results are illustrated in Fig.13. It can be seen that the differential power processed by passives in the ZSI is higher than that in a boost converter, especially for higher boost factor. It is important to note that the analysis is done for a switching period and does not take switching frequency into account. In reality, the switching frequency seen by the passives in a ZSI is 6 times the PWM frequency of the inverter switches whereas the switching frequency seen by the passives in the boosted inverter is set by the PWM frequency in the boost converter stage. Nonetheless, Fig.13 provides insight into the stress on the passives for different boost factors in ZSI. Boost factors should be limited below 2 to keep stress on the passives reasonable.



Figure 13: Passives Differential Power Comparison between ZSI and boost converter.

## **Z-Source Inverter Design and Implementation**

## **Circuit Design and Layout**

The specifications of the ZSI prototype are listed in Table 1. The selection of passives and switching devices are presented in Table 2.

Input Voltage	24V - 48V
Max Power	1.5kW
Max Boost Factor	2
Voltage Ripple of V <sub>bus</sub>	3%
Current Ripple of Inductors	20%
Switching Frequency	20kHz
Efficiency	>95% for most operating points

#### Table 1: E-bike ZSI Specifications

Components	Part/Value	Features
Inverter Switches	IRFB4110	Vdss = 100V, Id = 120A, Rds(on) =
		3.7mOhm
Source Diode D <sub>1</sub>	APT60S20	200V 75A Schottky with fast recovery
Inductors L <sub>1</sub> , L <sub>2</sub>	$L_{tot} = 12uH$	Custom Coupled Inductor Design
Capacitors $C_{in}, C_1, C_2$	40uF	Paktron Film Capacitor with low ESR/ESL
Gate Drive IC	UCC27211	
Rg	22 Ohm	Turn-on time constant = 220ns
Rt, Ct	100 Ohm, 1nF	Turn-off time constant = 100ns

#### Table 2: ZSI Component Selection

The inductor design deserves some discussion. The two inductors  $L_1$  and  $L_2$  are wound in a bifilar fashion on the same toroidal core to achieve tight coupling. Since the current flowing through the two inductors are identical, the coupled inductor design doubles the inductance of each winding [7]. Therefore, the total number of turns required to build the coupled inductor is half of that of two separate inductors. This design is critical to reducing the size of the inductors in a ZSI.

The gate drive circuits are shown in Fig.14. The gate resistor  $R_g$ , turn-off timing resistor and capacitor,  $R_t$  and  $C_t$  are chosen to achieve a desired turn-on and turn-off speed of the switching devices. The timings are chosen to balance switching loss and voltage overshoot/undershoot. The pnp is used to provide a low impedance path to ground when the power MOSFET turns off to prevent parasitic turn-ons.



Figure 14: Gate Drive Circuit

As discussed in section 2.3, to mitigate voltage spikes during switching, the size of the commutation current loop needs to be kept to a minimum. Fig.15 shows a picture of the assembled board. Capacitors  $C_{in}$ ,  $C_1$  and  $C_2$  are mounted on either side to reduce the loop inductance. To ensure that each phase has a short low impedance path, parallel capacitors and diodes are distributed evenly among the three phases.



Figure 15: Assembled ZSI Testing PCB

#### **Minimum Switching Space Vector Modulation**

This section introduces the *minimum switching space vector modulation* for a ZSI. Without loss of generality, an example is used to illustrate this control method. Without overmodulation or boost, the maximum AC phase voltage magnitude that can be generated is  $0.5V_{in}$ . By using overmodulation, we can increase this by 15% to a value of  $0.577V_{in}$ . Any AC voltage magnitude beyond  $0.577V_{in}$  cannot be generated without voltage boost or causing distortion. Suppose the objective is to generate 3 phase AC voltages of magnitude  $0.667V_{in}$ , which is another 15% more than  $0.577V_{in}$ . In order to generate this using the *constant boost SVM*, a constant shoot-through duty cycle of 0.12 and a constant modulation depth of 0.746 (= 0.866-0.12) are used. In the *minimum switching SVM* however, time-varying modulation depth and shoot-through duty cycle are used. Fig.15 compares the modulation depth and shoot-through duty cycle of the *constant boost SVM* and the *minimum switching SVM* in one output period.



Figure 15: Shoot-through Duty Cycle and Modulation Depth Comparison

Again, these two control methods can be illustrated on a space vector diagrams. In Fig.16a, *constant boost control* with a constant shoot-through duty cycle of 0.12 is shown. The blue traces show the modulation depth trajectory, which is a circle with constant radius. In the *minimum switching space vector modulation* shown in Fig.16b, instead of leaving the traditional zero states near the vertices unconverted, the algorithm utilizes them as active states. To generate sinusoidal output, we use time-varying boost factor to compensate for the time-varying modulation depth. The algorithm is detailed in Appendix 2.



Figure 16(a): Constant Boost SVM Example

Figure 16(b): Minimum Switching SVM Example

The *minimum switching space vector modulation* is superior to the *constant boost control* because of the elimination of the traditional zero states, which can be interpreted as the converter idle state. For  $\alpha = 30 + 60$ n degrees where n is an integer from 0 to 5, the modulation depth and shoot-through duty cycle for the two control schemes are exactly the same. This is because *constant boost control* already utilizes all zero states at those angles. These are also the angles at which the most amount of boosting is required. Therefore, the two control methods have the same worst-case differential power. However, as the *minimum switching SVM* uses less boosting at all other angles, it places less average stress on the devices and passives. To have a more quantitative comparison, we compare the converter best-case differential power and the average differential power over one output period in Appendix 3. The results are summarized in Table 3.

		D	
	Worst Case	Best Case	Average over
			e
			one output
			one output
	$(\alpha = 30 + 60n)$	$(\alpha = 60n)$	
		(0. 001)	period
			1
Constant Boost SVM	0.6758	0.6758	0.6638
Constant Doost S v Ivi	0.0750	0.0738	0.0058
Min Switching SVM	0 6758	0	0 4526
	0.0720	0	0.1020

**Table 3: Normalized Converter Differential Power Comparison** 

Fig.17 shows the average differential power comparison between the two modulation strategies. From the above analysis, we expect a loss reduction in the passives in addition to the 1/3 switching loss reduction.



Fig. 17: Average Differential Power Comparison between Constant Boost and Minimum Switching SVM

## **Experimental Results**

#### **Z-Source Inverter Modes of Operation**

A 1.5kW Z-source inverter with specifications listed in Table 1 has been designed, built and tested. During the first phase of testing, the *constant boost control* is used to evaluate the performance of the ZSI. Next, the proposed minimum switching SVM is used to demonstrate its operation and advantages over the constant boost control.

A ZSI has three main modes of operations: self-boost (DCM) mode, no-boost mode and boost mode. The self-boost mode or DCM occurs under light load conditions even without intentional insertion of shoot-through states. The boost occurs with the turn-on of body diodes of the MOSFETs in a phase leg when the inductor ( $L_1$  and  $L_2$ ) currents drop below the output current due to ripple in each PWM period. This scenario is illustrated in Fig.18 and waveforms showing the self-boost events are in Fig.19. As long as the maximum boosted voltage does not exceed the voltage rating of the switching devices, this self-boost mode does not present significant challenges to the design. In fact, this mode is ideal for high-speed coasting on an ebike with direct drive permanent magnet motors where the back-EMF of the motor exceeds the battery voltage.



Figure 18: Self Boost Mode Equivalent Circuit



Figure 19: Self-Boost Mode Waveforms. The time scale is 5us/div. The scales for the yellow, green, red and blue waveforms are 50V/div, 20V/div, 10V/div and 10V/div respectively. There is no shoot-through since the two gate signals (red and blue) are never both high. However, the inverter link voltage goes down to zero in the parasitic boost mode regions, suggesting the output has been shorted by the turn-on of the body diodes in all phase legs. The oscillations in the inverter link voltage (yellow) and switching node voltage (green) are the classical DCM behaviors.

The no-boost mode is used when the output voltage can be generated without the need of voltage boost. The control and circuit behavior in this mode is identical to those of a voltage source inverter except the dead time can be set to zero since shoot-through no longer presents a reliability issue. Operation in this state is the most efficient since the additional losses associated with the use of shoot-through states are not incurred. However, due to the parasitic inductance of the high frequency loop, the voltage overshoot on MOSFET turn-off is significant. Fig.20 illustrates the waveforms in this mode of operation.



Figure 20: no-boost mode waveform. The time scale is 10us/div and vertical scales for the waveforms are identical with those in Fig.19. Due to the absence of shoot-through states, the inverter link voltage never goes to zero. The voltage overshoot on MOSFET turn-off is significant.

The boost mode is used to enable generation of even larger voltage output. Operation in the boost mode is slightly more inefficient compared to the no-boost mode. This is primarily due to the higher MOSFET conduction loss during the shoot-through states where current of magnitude  $2I_L$  flows through both MOSFETs in a phase leg. There is also more  $C_{oss}$  loss: upon entering the shoot-through state where one phase leg is shorted, the output capacitances of all the MOSFETs are discharged. Upon transitioning into a non shoot-through state, the  $C_{oss}$  of one MOSFET per phase leg needs to be charged up to a voltage equal to the inverter link voltage. The  $C_{oss}$  loss in the boost mode is approximately 6 times that in the no-boost mode because there are 6 shoot-through events in a PWM period. However, this loss is very small, less than 1% of total system loss in the boost mode. The advantage of this operation is that the 3 parallel  $C_{oss}$  act as a snubber capacitance and reduce voltage overshoot on MOSFET turn-off. Fig.21 illustrates the waveforms in the boost mode.



Figure 21: boost mode waveform. The time scale is 5us/div and vertical scales for the waveforms are identical with those in Fig.19 and Fig.20. Shoot-through occurs when both the high gate signal and the low gate signal are high, where the inverter link voltage and phase voltage go to zero. The inverter link voltage is boosted to around 52V, which is 1.45 times the 36V input voltage. The voltage overshoot on MOSFET turn-off is significantly reduced.

Efficiency and voltage overshoot measurements are carried out on the ZSI prototype. Table 4 summarizes the testing conditions. The ZSI operates in self-boost mode (DCM) for output phase current below 12Arms. Then as the modulation depth is increased gradually to 75% without using shoot-through, the ZSI operates in the no-boost mode for output phase current between 12Arms to 16Arms. Next, the shoot-through duty cycle is increased gradually from 0% to 25%; at 25% shoot-through duty cycle, the ZSI achieves the max boost factor of 2. Fig.22 shows the efficiency plot versus output currents. Fig.23 shows the overshoot voltage versus output currents.

Input Voltage	36V
PWM Frequency	20kHz
3 phase output LC filter	L = 200 uH, C = 15 uF
Load	2-ohm resistors in delta connection
Electrical Load Frequency	60Hz
Power Factor	Near Unity
Phase Current	7Arms to 33Arms
Power Output	100W to 1000W

Table 4: Testing conditions for efficiency and voltage overshoot measurements



Figure 22: Efficiency vs Output Phase Current



Figure 23: Voltage Overshoot vs Phase Current in Different Modes

#### **Z-Source Inverter Loss Analysis**

The inverter achieves over 95% efficiency for most of its operating points. This section presents the loss breakdown and evaluates potential circuit or control modifications that can further improve the efficiency of the converter. Fig. 24 shows the loss breakdown analysis in a pie chart. The test conditions are the same as listed in Table 4 and the output phase current is 16.5 Arms, resulting in an output power of 550W.



Figure 24: Loss Breakdown Analysis

Losses in the inductor and semiconductor devices account for most of the loss in the system. Thermal measurements on the heatsinks attached to the MOSFETs and diodes have been carried out to validate the analysis on the semiconductor losses. The MOSFET switching losses mainly stem from the overlap of voltage and current during device turn-on/turn-off. Due to the voltage overshoots and undershoots caused by the parasitic inductance, turn-on and turn-off times are intentionally slowed down to reduce them at the expense of higher switching loss. To further improve the efficiency of the converter, one practical approach is to install MOSFETs in

parallel with the source schottky diode  $D_1$  to reduce diode conduction losses. Furthermore, the *minimum switching space vector modulation* could be used to reduce switching losses.

#### Minimum Switching Space Vector Modulation Results

This section presents the comparison between the *minimum switching SVM* and the *constant boost SVM*. The two schemes were run to generate an AC voltage of magnitude 0.667V<sub>in</sub> at 60Hz from 36V power supply. Due to the voltage drop across the cable between the power supply and the ZSI prototype, the input voltage is effectively 32V. Shown in Fig.25 is the output line-to-line voltage waveform generated by the *constant boost SVM*, which serves as a benchmark. This waveform is collected after the output LC filter. Shown in Fig.26 is the output line-to-line voltage waveform generated by the *minimum switching SVM*. The almost identical waveforms indicate that the *minimum switching SVM*, which uses time-varying modulation depth and shoot-through duty cycle, is able to achieve the same output as the popular *constant boost SVM*.



Figure 25: Line-to-line voltage output generated by the *constant boost SVM*. The time scale is 5ms/div and vertical scale is 10V/div.



Figure 26: Line-to-line voltage output generated by the *minimum switching SVM*. The time scale is 5ms/div and vertical scale is 10V/div.

The inverter bus ripple and gate waveforms are shown in Fig.26. The orange and blue waveforms on the bottom show the gate-to-source voltage of the high-side and low-side MOSFETs in a single phase leg respectively. The orange waveform is noisier because it is not directly measured but obtained by subtracting the source voltage from the gate voltage. Each of these two signals is held high without switching for 1/3 of the 60Hz period. The green waveform measures the phase voltage with respect to the bottom rail. When  $V_{gs}$  of the bottom MOSFET (blue) is held high, the phase voltage is zero. If the phase voltage is zero.



Figure 26: Minimum switching SVM waveforms. The time scale is 2ms/div and the vertical scales are labeled in the figure. The waveforms from top to bottom are inverter link voltage, switching node voltage in a phase, high side Vgs and low side Vgs in the same phase leg. The 6-pulse appearance on the inverter link voltage envelope (yellow) is evidence for the implemented time-varying shoot-through duty cycle.

Fig.27 shows that the minimum switching symmetric SVM reduces the total system loss by 20% compared to the constant boost SVM in the tests conducted. The loading conditions in these tests are the same as in Table 4. Input voltages at 24V, 28V, 32V and 36V are used for each scheme to generate the data points for comparison.



Figure 27: Power Loss Comparison between Minimum Switching SVM and Constant Boost SVM

## Conclusion

This technical report presents the analysis, circuit design and control design of a Z-source inverter for an electric bike. The original analysis on ZSI based on differential power provides insight into the disadvantages of the topology and provides a quantitative measure of the boost factor that can be practically used. The newly developed *minimum switching SVM* uses variable modulation depth and variable boost to reduce converter loss significantly. Due to the unavailability of a dynamometer, all the experiments were performed on an RL load. However, the proposed space vector modulation can be easily fitted into a standard field oriented control scheme for driving AC machines. The *minimum switching SVM* control used for the initial performance evaluation only considers a single operating point but it could be easily extended using the algorithm in Appendix 2.

This project demonstrates that the ZSI is a viable candidate for high performance e-bike controllers. The use of a ZSI can extend the constant torque region and achieve higher top speed in an e-bike. Without voltage boost, this could only be achieved by either using larger battery packs or switching to motors that produce less torque. The main disadvantages of the topology are the volume and cost of the added passives in the impedance network front-end. If only modest boost is required (< 2X), which is the case for an e-bike, these disadvantages may be a small price to pay for the higher performance and more flexibility in designing e-bike systems.

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# Appendices

## 1. Differential Power Analysis for ZSI

Each of Inductors  $L_1, L_2$ :

$$P_{diff_{L12}} = V_{cap} \times I_L \times d = P_o \times \frac{d(1-d)}{1-2d}$$

Each of Capacitors C<sub>1</sub>, C<sub>2</sub>:

$$P_{diff_{C12}} = V_{cap} \times I_L \times d = P_o \times \frac{d(1-d)}{1-2d}$$

Capacitor C<sub>in</sub>:

$$P_{diff\_cin} = P_o \times d$$

#### 2. Minimum Switching SVM Algorithm

To eliminate all zero states in the control, we can express the output AC magnitude as a function of *d* the shoot through duty cycle and  $\alpha$  the angle labeled in Fig.15a. Note that in the following equations we will assume common mode injection is utilized.

$$V_{AC} = M \times B \times \frac{V_{in}}{\sqrt{3} \cos(\frac{\pi}{6} - \alpha)}$$

Substituting  $M = l \cdot d$  and  $B = \frac{1}{1 - 2d}$ 

$$V_{AC} = \frac{1-d}{1-2d} \times \frac{V_{in}}{\sqrt{3} \cos(\frac{\pi}{6}-\alpha)}$$

Given a desired AC voltage vector and angle  $\alpha$  which is either measured with a hall sensor or estimated with an observer, *d* can be solved using the above equation.

#### 3. Differential Power Comparison Between Control Methods

For constant boost SVM,

$$V_{AC} = \frac{1-d}{1-2d} \times \frac{V_{in}}{\sqrt{3}}$$

For minimum switching SVM,

$$V_{AC} = \frac{1-d}{1-2d} \times \frac{V_{in}}{\sqrt{3} \cos(\frac{\pi}{6}-\alpha)}$$

For a certain  $\frac{V_{ac}}{V_{in}}$ , we can calculate the *d* for the two control strategies. In the case of *minimum switching SVM*, *d* is a function of  $\alpha$  as well. The following MATLAB script is used to evaluate the average differential power of the converters.

%% Appendix 3 Converter Differential Power Calculation under Constant Boost SVM and Minimum Switching SVM

%Comparison based on the example in 3.2

%For constant boost SVM, shoot-through duty cycle is constant at 0.12.

%For minimum switching SVM, shoot-through duty cycle is time-varying and presented in appendix 2

alpha = linspace(0,pi/3,1000); %1000 points from 0 to 60 deg

AF = cos(pi/6-alpha); %AF = angle factor, calculated for ease of calculation later

ST duty cycle = (AF\*2/sqrt(3) - 1)./(AF\*4/sqrt(3)-1); %Time-varying ST duty cycle for the example

Pint\_ZSI = @(ZSI\_d) ((2\*(1-ZSI\_d).\*ZSI\_d./(1-2\*ZSI\_d))+(2\*ZSI\_d.\*(1-ZSI\_d))./(1-2\*ZSI\_d)+ZSI\_d); %Converter Differential Power as a function of ST duty cycle

Max\_ST\_dutyCycle = max(ST\_duty\_cycle);

Min\_ST\_dutyCycle = 0;

Pint\_consboost\_worst = Pint\_ZSI(Max\_ST\_dutyCycle);

Pint\_consboost\_best = Pint\_consboost\_worst;

Pint\_consboost\_average = Pint\_consboost\_worst;

Pint\_minsw\_worst = Pint\_ZSI(Max\_ST\_dutyCycle);

Pint\_minsw\_best = Pint\_ZSI(Min\_ST\_dutyCycle);

Pint\_minsw\_average = mean(Pint\_ZSI(ST\_duty\_cycle));

fprintf('Average normalized differential power for constant boost is %d and that for minimum switching is %d\n',Pint\_consboost\_average,Pint\_minsw\_average);

%% Instead of working on this specific example, examine general case; want to plot average diff power vs AC magnitude for these two modulation strategies

d\_array = [];

for i = 0.667:0.01:2

syms d

eqn = (1-d)/(sqrt(3)\*(1-2\*d)) == i;

sol\_d = solve(eqn,d);

d\_array = [d\_array,sol\_d];

end

```
Pint_consboost_average_array = Pint_ZSI(d_array);
```

Vac\_over\_Vin = 0.667:0.01:2;

plot(Vac\_over\_Vin,Pint\_consboost\_average\_array)

%%

Pint\_minsw\_average\_array = [];

for i = 0.667:0.01:2

syms d

d\_period = [];

for alpha = 0:pi/300:pi/3

 $AF = \cos(pi/6-alpha);$ 

eqn = (1-d)/(sqrt(3)\*(1-2\*d)\*AF) == i;

sol\_d = solve(eqn,d);

d\_period = [d\_period,sol\_d];

end

Pint\_minsw\_average\_each = mean(Pint\_ZSI(d\_period));

Pint\_minsw\_average\_array = [Pint\_minsw\_average\_array,Pint\_minsw\_average\_each];

end

Vac\_over\_Vin = 0.667:0.01:2;

plot(Vac\_over\_Vin,Pint\_minsw\_average\_array)