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GaN-based Synchronous Buck Converter With Zero-Voltage Resonant-Transition Switching

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Abstract: GaN power switching devices are promising candidates for high switching frequency and high efficiency operations due to their lower on-resistance and faster switching capabilities compared to conventional silicon power devices. As the switching frequency increases up to the MHz-level, soft switching plays an important role to further minimize the switching losses and improve the efficiency.

In this paper, a GaN-based synchronous buck converter operating with zero-voltage resonant-transition (ZVRT) switching in synchronous conduction mode is proposed. The ZVRT switching converter offers a favorable trade-off between switching and conduction losses especially in GaN-based DC-DC converters.

The efficiency of the ZVRT switching converter providing 20 W output power from 28 V input voltage improves up to 7% at 3 MHz switching frequency.

Index Terms: GaN-based converter; buck converter; high switching frequency; soft switching technique; zero-voltage resonant-switching converter;

I. INTRODUCTION

Wide bandgap (WBG) semiconductors such as gallium nitride (GaN) and silicon carbide (SiC) are commonly known to be the next generation of power switching devices due to their superior characteristics compared to conventional silicon devices. These new power devices are capable of high-speed switching, high temperature, and low conduction and switching losses operations. The benefits of using WBG based devices in hard-switched converters has been investigated and quantified for various applications by researchers [1]. However, the applications of WBG, especially GaN devices, in soft- switched topologies are less studied. This research paper aims to propose the application of Zero-Voltage- Resonant-Transition (ZVRT) technique in the GaN-based synchronous buck converter to further take advantage of the superior properties of GaN devices.

For electric vehicle (EV) applications, Toyota reported a new SiC power converter for use in automotive power control units (PCU). With this new converter, the fuel efficiency improves by 10% compared with the Si-based EV. This new technology also enables 80% size reduction in the PCU with respect to the previous version. For medium voltage applications, Cree, Inc. recently developed 10 kV, 120 A SiC power MOSFETs and 1700V Schottky diodes which can replace conventional IGBTs and Si-based diodes. At 20 kHz, the switching loss of a SiC MOSFET is 18 times lower than that of a Si-based IGBT and the conduction loss is almost half [2]. In the case of GaN power devices, the product availability is less than that of SiC, especially in high voltage applications due to its inherent material characteristic (high electron mobility) and more expensive manufacturing cost. However, GaN devices are more suitable for 600 V or less voltage level and lower power applications than SiC due to its high electron mobility and size advantage. One of the GaN device manufacturers, Efficient Power Conversion (EPC) Corporation released a 300 V, 2.7 A enhanced mode power transistor, which can be applied in various applications where high frequency switching is essential. Regarding concern for the price of WBG devices, they are expected to be cheaper than Si devices in 2016 and this will dramatically boost the transition from Si devices to WBG devices. For applications lower than 200 V, there are abundant options of GaN devices that can be applied to the MHz-level DC- DC converters.

For high switching frequency, smaller size, and lightweight DC-DC converters, soft switching techniques are essential and numerous classes of resonant-switch or quasi-resonant converters have been actively proposed and also researched [3]. The basic concept and the experimental results of a zero-voltage-switched quasi-resonant-wave (ZVS-QSW) converter, which is also called zero-voltage resonant-transition (ZVRT) switching converter, operating at 1 MHz is presented in reference [4]. This soft switching can be obtained by choosing an appropriately valued inductor such that the peak-to-peak inductor current (current ripple) is always higher than twice the average output current [3-5]. This technique is relatively simple to achieve since it does not require either additional passive and active components or a complicated control loop [4]. However, the main disadvantage of this converter is the high conduction losses due to the two times higher current ripple [3]. Because of the high conduction losses, this technique is not suitable for applications where minority carrier devices, such as IGBTs, are used [3].

Nevertheless, in the case of GaN devices, this technique can offer significant benefits especially in high switching frequency converters due to their lower on-resistance. With GaN-based ZVRT switching converters, the low switching losses can be achieved while not significantly increasing their conduction losses. Furthermore, a current spike due to the high dv/dt of the GaN device and the output capacitance, C_{oss} can be decreased with soft switching and it also helps to minimize the switching losses. Although GaN-based converters with various soft switching techniques are presented in other references [4-7], the GaN-based ZVRT switching converter has not been proposed and studied.

This research paper contributes to close the knowledge gap for soft-switched GaN based devices by presenting a GaN-based synchronous buck converter with ZVRT technique. The paper is organized in the following way: Section II describes the general operating principle of a ZVRT switching converter. Section III highlights the benefits of ZVRT technique with loss and efficiency analysis. A conclusion is drawn in Section IV.

II. ZERO-VOLTAGE RESONANT-TRANSITION SWITCHING CONVERTER

The synchronous buck converter is being extensively used in low output voltage DC power applications. The schematic of the converter is shown in Fig. 1. By commutating a freewheeling current through a switching device having low on-resistance instead of a diode, the overall efficiency of the converter can be improved. However, as the switching frequency increases up to the MHz-level, it requires soft switching to minimize its switching losses. The ZVRT switching converter uses a properly sized inductor such that the inductor current always crosses zero as seen in Fig. 2. The switches Q_1 and Q_2 turn on and off when the current flows through their body diodes to obtain zero-voltage switching (ZVS). The detailed operation is explained in references [3-4]. To achieve soft switching with the ZVRT switching converter, an appropriately sized inductor value is the most important design consideration. The inductor value needs to be the maximum inductance that enables the ZVRT switching while keeping the inductor current ripple as small as possible. The inductor value can be estimated by

$$L_1 = \frac{1}{K}\left(1 - \frac{V_{out}}{V_{in(min)}}\right) R_{1(min)} T \qquad (1)$$

where V_{in} and V_{out} are the input and output voltages of the buck converter and $R_{1(min)}$ and T are the output load resistance and the switching period. The coefficient K is the ratio between the peak-to-peak inductor current ripple and the average inductor current. The value K must be greater than 2 to have the negative current for soft switching. In general, it is set to be 4 to have three to one ratio of the turn-on and turn-off transitions for the switching devices [4]. Using this equation and the specifications of the buck converter given in Table I, the inductor value of 36.76 nH is obtained. In this simulation, 36 nH is used.

TABLE I
SPECIFICATION OF SYNCHRONOUS BUCK CONVERTER

V_{in}	V_{out}	V_{ripple}	f_{SW}	P_{out}
28 V	3.3 V	100 mV (±3%)	3 MHz	15 – 25 W

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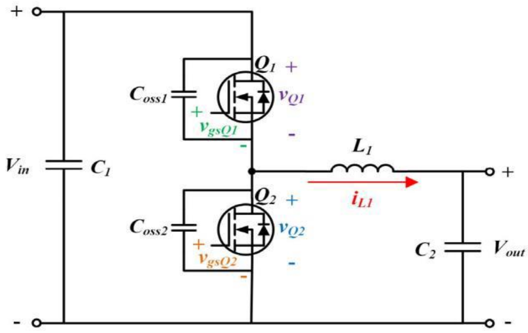

Fig. 1. The schematic of the synchronous buck converter

A. Topology and Specifications

The ZVRT switching converter used in the simulation has 28 V input voltage and 3.3 V output voltage. Depending on the dead-time applied, an additional Schottky diode can be used to minimize the body diode loss of the GaN FET. The average output power is about 20 W and the voltage peak-to-peak ripple is set to be 3%. The GaN device used in this simulation is the EPC2015 from EPC Corporation as shown in Table II. Using GaN switching devices instead of Si devices in a synchronous buck converter helps to minimize conduction losses due to the low on-resistance. Although a synchronous buck converter is not always more efficient than a non-synchronous buck converter depending on its output power level and switching frequency [9], the lower on resistance of GaN devices make a synchronous converter more efficient in wider range of power and switching frequency applications. In addition, it is possible to increase the switching frequency above MHz-level enabling the size reduction of passive components and the entire converter. The lower conduction and switching losses also lead to a decrease in device stress and an increase of device reliability. However, if the optimal operating condition is not realized, especially in high frequency operations, the severe switching loss due to the current spike will degrade the overall efficiency of the converter.

Table III and IV show the specification of the filter inductors and capacitors. First of all, 36 nH and 150 nH inductors with ferrite core are used to compare the efficiency of the conventional and ZVRT converter. However, it is found out that the core loss of the inductor is significantly high due to the high switching frequency and current ripple. To further improve the efficiency, the air core inductors with 33 nH and 155 nH inductance are also investigated. The same capacitor is used in both the conventional and ZVRT switching converters for fair comparison.

TABLE II
CHARACTERISTICS OF GAN SWITCHING DEVICE

Part Number	V_{DS}	R_{DS}	I_{DS}		V_{GS}	T_J
			Cont.	Pulsed (T=3003s)		
EPC2015	40 V	4 mö	33 A	150 A	5 V	-40 to 150 °C

TABLE III
SPECIF IC ATION OF FILTER INDUCTOR (L1)

	Conventional Switching		ZVRT Switching	
Part Number	SLC7649S -151KL	2014VS-151NME	SLC7649S-360KL	2014VS-33NME
Inductance [nH]	150	155	36	33
Resistance [mö]	0.18	0.63	0.18	1.44
Irms [A]	39.0	31.0	39.0	32.5
Isat [A]	27.0	N/A	100.0	N/A
Core Material	Ferrite	Air	Ferrite	Air
Manufacturer	Coilcraft	Coilcraft	Coilcraft	Coilcraft

TABLE IV
SPECIF IC ATION OF FILTER CAPAC IT OR (C1)

	Conventional Switching	ZVRT Switching
Part Number	C1005X5R1A105K050BB	C1005X5R1A105K050BB
Capacitance [3F]	47	47
Resistance [mö]	3	3
Manufacturer	TDK	TDK

B. Trade-off between Switching and Conduction Losses

The switching frequency of the ZVRT converter needs to be carefully determined since there is a trade-off relationship between switching and conduction losses of the switching devices. This converter enables soft switching by increasing current ripple until it reaches synchronous conduction mode where the inductor current flows bidirectional. However, this high ripple current increases the conduction loss of the switching device since the AC component of the conduction loss increases [4].

$$P_{cond} = P_{DC} + P_{AC} \qquad (2)$$

$$P_{cond} = (I_{out}^2 + \frac{I_{Lripple}^2}{12})R_{DS} \qquad (3)$$

$$P_{cond} = (I_{out}^2 + \frac{(KI_{out})^2}{12})R_{DS} \qquad (4)$$

Using (4), the conduction loss of the device can be calculated [4]. In this equation, *Iout* is the output current of the converter and *ILripple* is the amplitude of the inductor current ripple. *K* is the ripple current ratio and *Rds* is the on-resistance of the switching device.

To take advantage of the ZVRT converter, the switching loss must be higher than the conduction loss and the switching loss can be approximated by

$$P_{switch} = 2(C_{oss}V_{in}^2 + V_{in}I_{out}t_r)f_{sw} \qquad (5)$$

where C_{oss} is the output capacitor of the switching device and V_{in} is the input voltage. t_r is the average switching transition time and f_{sw} is the switching frequency [4]. The minimum switching frequency that the switching loss becomes larger than the conduction loss is about 120 kHz as shown in Fig. 2. Since the switching loss increases as the switching frequency increases, 3 MHz switching frequency will offer a significant benefit in ZVRT converter.

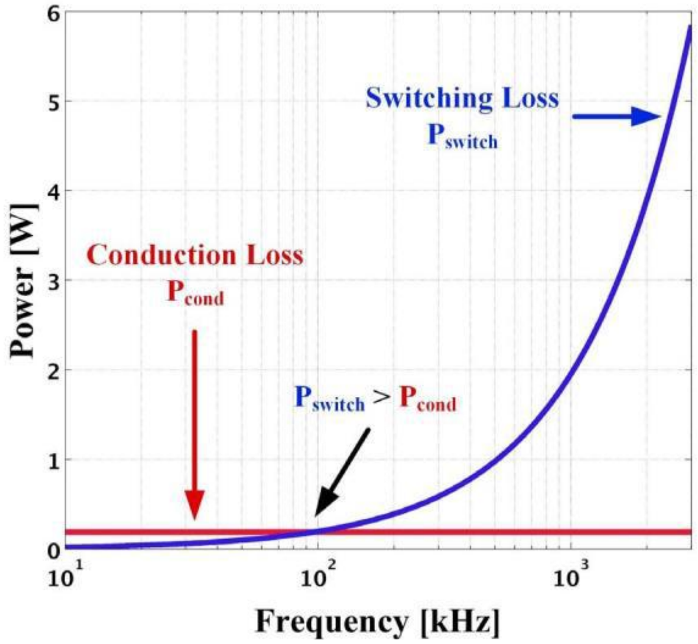

Fig. 2. Estimation of switching and conduction losses from 10 kHz to 3 MHz switching frequency range (*Vin* = 28 V, *Iout* = 4.5 A, *Coss* = 600 pF, *tr* = 4 ns, *ILripple* = 27 A)

C. Switching Transition

The inductor current, gate voltage, and the switch voltage waveforms are shown in Fig. 3. The dead-time needs to be adjusted within the time ranges of *tsw1* and *tsw2* to achieve soft-switching of *Q1* and *Q2* respectively. The switching modes of ZVRT converter are shown in the Fig. 4.

Mode 1 – Both switches *Q1* and *Q2* are off and the inductor current is flowing in a reverse direction. This current charges the output capacitor, *Coss2*, of *Q2* during the dead-time until the voltage reaches the input voltage *Vin*. If the dead-time is longer than this ideal value (turning on *Q1* exactly at the moment when *vQ2* reaches *Vin*), *D1* (a body diode of *Q1*) starts to conduct. It causes diode conduction loss so that the conduction loss of *Q1*increases.

Mode 2 – When the output capacitor voltage v_{Q2} reaches the input voltage, the switch Q_1 turns on (zero voltage switching).

Mode 3 – At the beginning of this mode, the inductor current is flowing in the positive direction. When the switch Q_1 turns off, the inductor current starts charging the output capacitor, C_{oss1}, of Q_1 during the dead-time until the voltage v_{Q1} reaches the input voltage.

Mode 4 – The switch Q_2 turns on when v_{Q1} reaches the input voltage, and the forward direction inductor current flows through it. After the end of this mode, the full switching cycle is finished.

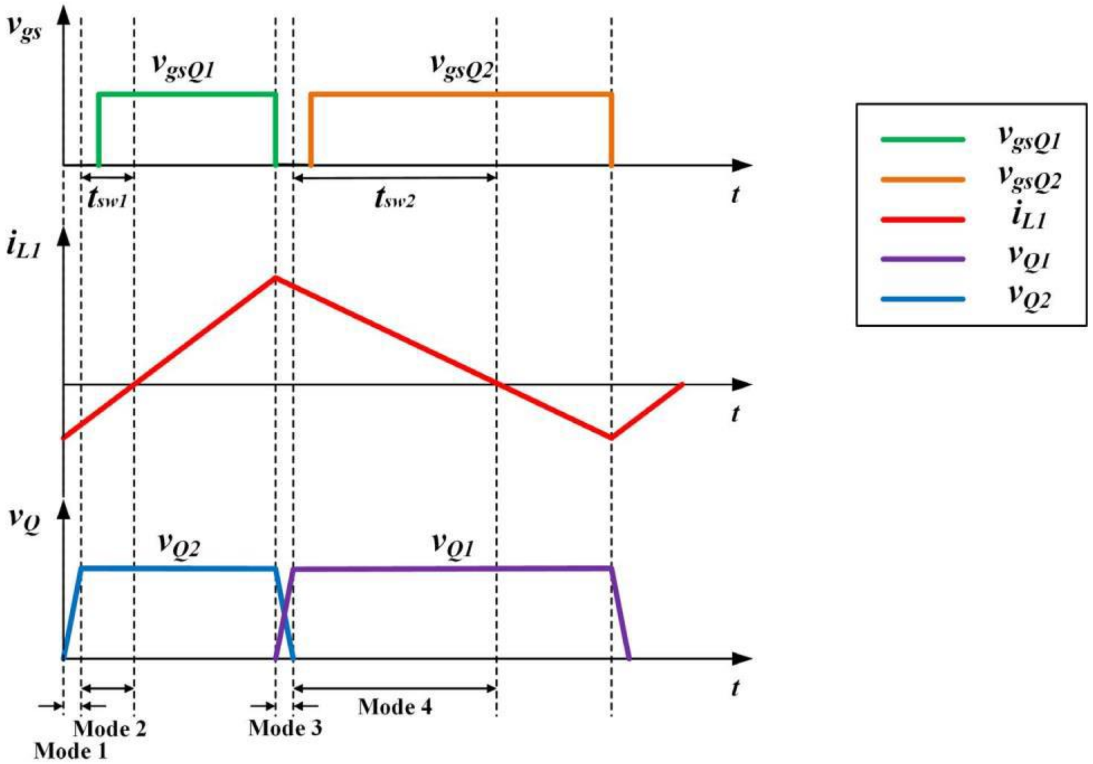

Fig. 3. Switching transitions of ZVRT switching converter (*vgsQ1* – gate voltage of *Q1*, *vgsQ2* – gate voltage of *Q2*, *iL1* – inductor current, *vQ1* – drain to source voltage of *Q1*, *vQ2* – drain to source voltage of *Q2*, *tsw1* – ZVS region of *Q1*, *tsw2* – ZVS region of *Q2*)

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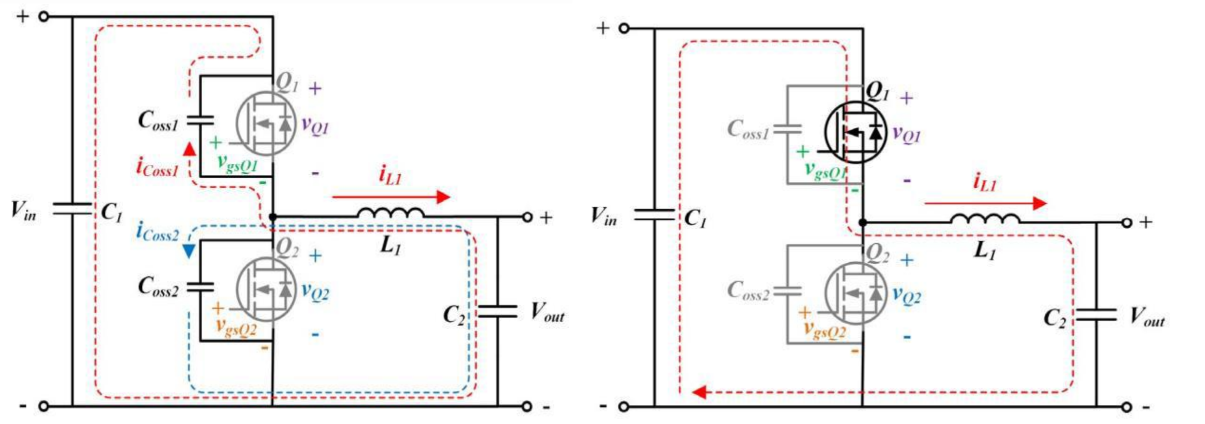
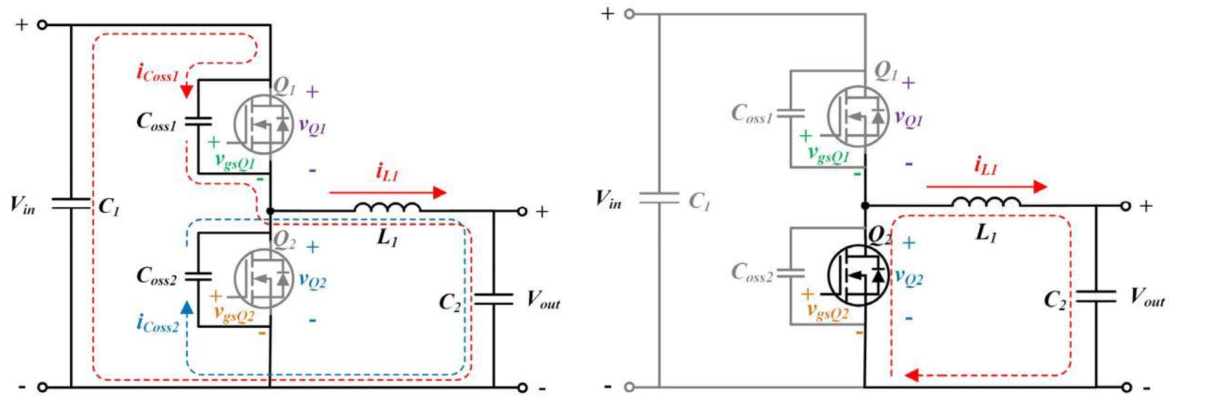


(a) (b)



(c) (d) Fig. 4. Switching modes of ZVRT switching converter

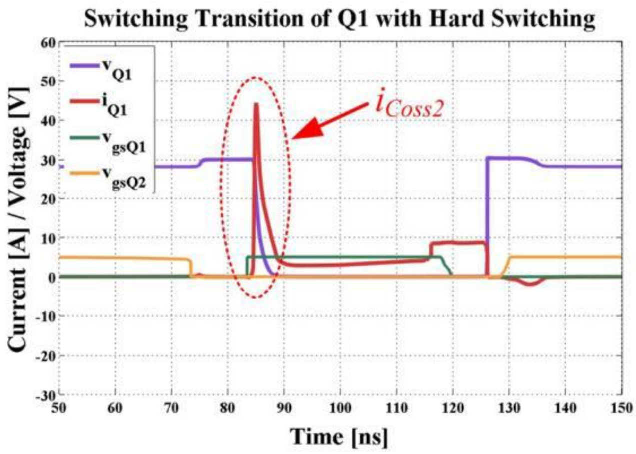
(a) Mode 1 - Q1 and Q2 are off (Coss1 is discharging and Coss2 is charging)
(b) Mode 2 - Q1 is on and Q2 is off
(c) Mode 3 - Q1 and Q2 are off (Coss1 is charging and Coss2 is discharging)
(d) Mode 4 - Q1 is off and Q2 is on

D. Comparison of On/Off Switching Transitions

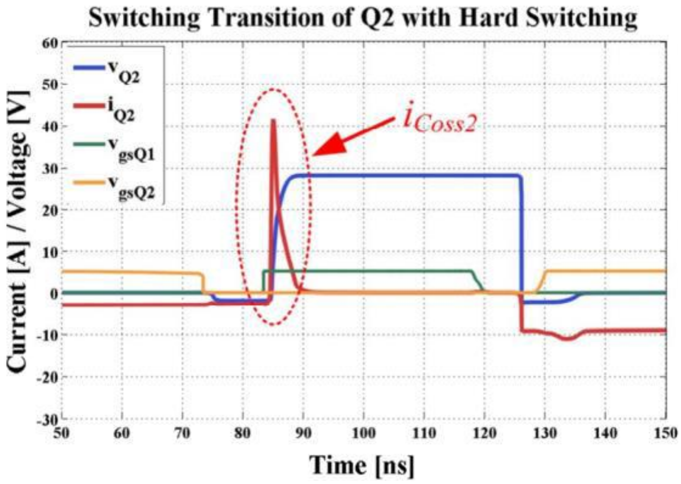
The on/off switching transitions of the top and bottom switches, *Q1* and *Q2*, are presented in Fig. 5. First, the synchronous buck converter with 150 nH inductor operating without soft switching shows a high current spike at the turn-on and turn-off transitions, as shown in Fig. 5 (a) and (b). This is due to the high dv/dt of the GaN device and the output capacitor, *Coss*.

$$i_{Coss} = C_{oss}\frac{dv}{dt} \qquad (4)$$

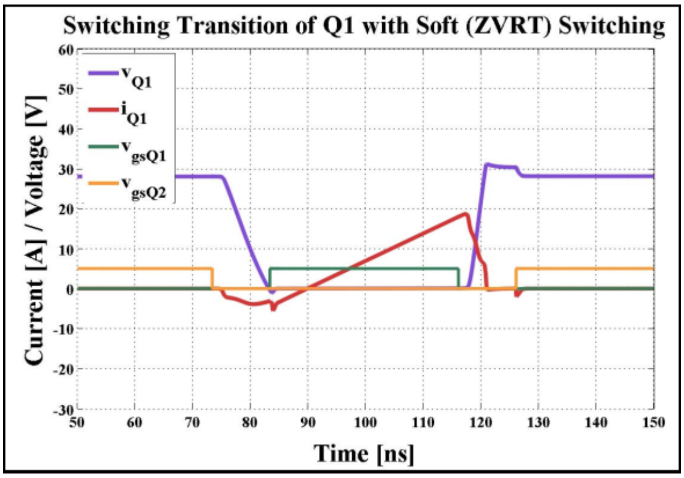
As seen in (4), the amount of current flowing into the output capacitor of Q_2 is estimated by the size of the C_{oss} and *dv/dt*. The C_{oss} and *dv/dt* of GaN device are significantly higher than that of Si device for the similar V_{ds} and I_{ds} and these characteristics cause the high current spike into Q_2 when Q_1 turns on. When the inductor current flows in a forward direction, C_{oss2} of switch Q_2 is discharged. This output capacitor is charged again when switch Q_1 turns on so that input voltage is applied to the switch node. At this moment, a high charging current, i_{Coss2}, flows into the output capacitor of Q_2 and causes the high switching loss as shown in Fig. 5 (a) and (b). In the case of a ZVRT switching converter with the 36 nH inductor, this high charging current does not appear because the current flows in a reverse direction when switch Q_2 turns on as shown in Fig. 5 (c) and (d). The inductor provides the charging current to the output capacitor of Q_2 so that the switching loss can be minimized. To fully charge the capacitor up to V_{in}, dead- time needs to be adjusted in accordance with the output load condition.



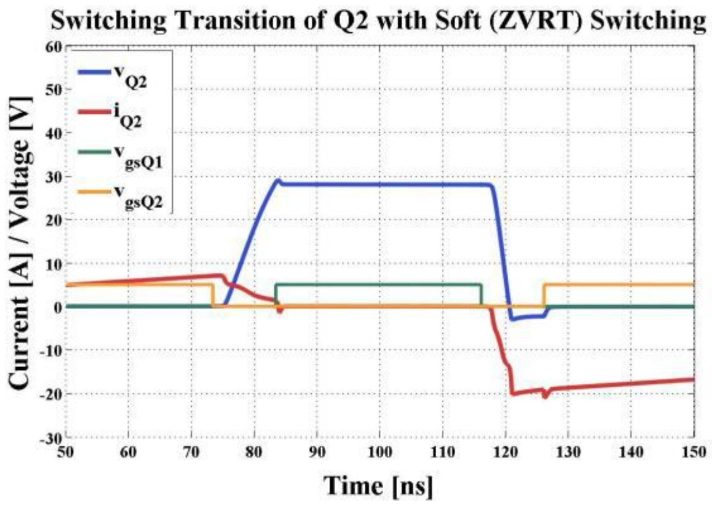
(a)



(b)



(c)



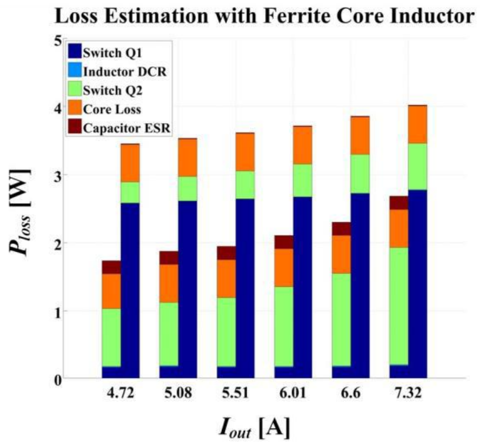
(d)

Fig. 5. (a) Current and voltage of switch *Q1*, *L1* = 150 nH, *fsw* = 3 MHz (conventional switching); (b) Current and voltage of switch *Q2*, L1 =150 nH, *fsw* = 3 MHz (conventional switching); (c) Current and voltage of switch *Q1*, *L1* = 36 nH, *fsw* = 3 MHz (ZVRT switching); (d) Current and voltage of switch *Q2*, *L1* = 36 nH, *fsw* = 3 MHz (ZVRT switching)

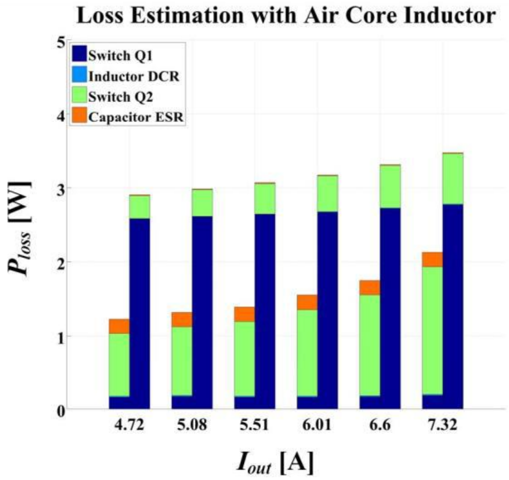
III. POWER LOSS AND EFFICIENCY COMPARISON

Figure 6 (a) and (b) show the overall converter losses with different inductor values and types. First of all, the ZVRT converter with 36 nH ferrite core inductor has significantly lower switching loss than that of the conventional converter with 150 nH ferrite core inductor. Especially the switching device loss of *Q1* is decreased from 2.6 W to 0.16 W due to soft switching. The switching device loss of *Q2* is increased due to the high reverse current flowing into the device at the switching transition. In addition, the capacitor conduction loss due to the equivalent series resistance (ESR) increases in ZVRT converter because of the high current ripple. The overall converter losses are decreased by 50% at maximum in ZVRT converter compared to the conventional converter. The overall efficiency of the converter is improved by 6.4% at maximum so that 90.8% efficiency is achieved in ZVRT converter with 36 nH ferrite core inductor. However, it is noted that there is a relatively high core loss of the inductor estimated by the core loss calculator from the manufacturer, due to the high switching frequency and high current ripple. To further improve the overall efficiency of the converter, the air core inductors with 33 nH and 155 nH are applied to both ZVRT and conventional converters. As seen in Fig. 6 (b), the overall converter losses are decreased by 30% in average which is equivalent to 3% overall converter efficiency improvement.

As seen in Fig. 6 (c), the ZVRT switching converter with ferrite core 36 nH inductor shows about 7% higher efficiency when compared to the converter with ferrite core 150 nH inductor at 3 MHz with the output current from 4.7 A to 7.34 A. The efficiency of both ZVRT and the conventional converters improve by 3% by using air core inductor so that the highest efficiency of 93.63% is achieved in ZVRT converter with 33 nH air core inductor. In the case of ZVRT converter, the overall efficiency decreases as the output current increases since the reverse current decreases. The reverse current plays an important role for soft switching as explained in the previous section. If the amplitude of the reverse current decreases, the dead-time needs to be increased, which in turn, causes high diode conduction loss of the switching device. It also causes higher switching loss of the switch *Q_2* especially when it turns off. On the other hand, the overall efficiency of the conventional converter increases as the output current increases. This is because the overall losses are not increasing as fast as the increase of the output power. However, at the worst case of 7.34 A output current, the efficiency of ZVRT converter is still 4.35% higher than that of the conventional converter.



(a)



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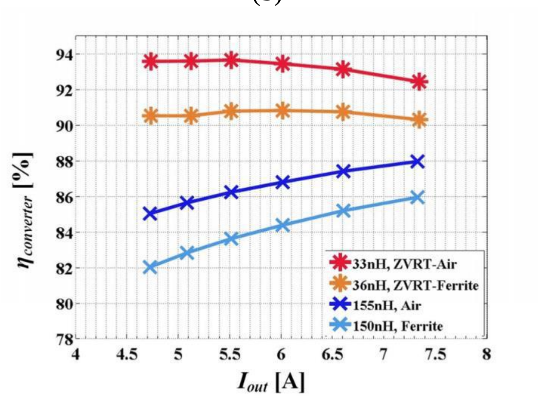

(c)

Fig. 6. (a) Power loss estimation of converters with 36 nH (left –ZVRT switching) and 150 nH (right – conventional switching) inductors with ferrite core; (b) Power loss estimation of converters with 33 nH (left – ZVRT switching) and 155 nH (right – conventional switching) inductors with air core; (c) Efficiency curves of converters with various inductor values and core materials (33 nH – air core and ZVRT switching, 36 nH – ferrite core and ZVRT switching, 150 nH – ferrite core and conventional switching, 155 nH – air core and conventional switching)

IV. CONCLUSIONS

This paper presents a ZVRT switching converter operating in synchronous conduction mode with lower switching losses and higher efficiency than that of a converter operating in continuous conduction mode. By properly sizing the inductor of the GaN-based synchronous buck converter for the ZVRT switching, the overall efficiency is improved through two means: minimizing the current spike and enabling soft switching. The high conduction loss due to the high inductor current ripple can be significantly minimized when it is applied to the GaN-based converter due to the low drain to source resistance, R_{ds}. It is also found out that the overall efficiency of the converter is improved by 3% by using an air core inductor instead of a ferrite core inductor due to the elimination of the large core loss. The overall efficiency improves by 7% at maximum at the switching frequency of 3 MHz and the total converter losses are decreased by 50% in average. As observed in the efficiency comparison of 4.73 A output current case, the ZVRT switching converter achieves better performance at light load condition due to relatively high amplitude of the reverse current which is necessary for soft switching.

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