# A Study of Multilevel Resonant DC-DC Converters for Conventional DC Voltage Bus Applications

Javad Khodabakhsh and Gerry Moschopoulos
Department of Electrical & Computer Engineering
Western University
London, Canada
jkhodaba@uwo.ca, gmoschop@uwo.ca

***Abstract*— Multilevel DC-DC topologies are used in applications where the DC bus voltage is high (i.e. 800 V- 1000 V). They can also be used in applications with conventional DC bus voltages, but this type of implementation has not been investigated, especially for multilevel DC-DC resonant converters. This paper is a study of multilevel resonant DC-DC converters for reduced DC voltage bus applications that tries to address this gap in the literature. In this digest, the basic operation of a series-resonant multilevel DC-DC converter is reviewed for ZVS and ZCS operation and for the case when the primary voltage and current are in phase with each other. Experimental results of a prototype for all three cases are then presented and conclusions are made.**

***Keywords—DC-DC resonant converter, Multilevel converter, Zero voltage switching, Zero current switching***

## I. INTRODUCTION

Multilevel converters are typically used in applications where converters switches are exposed to high voltage stresses. For DC-DC converters, the DC bus voltage tends to be about 800-1000V and the converters can be PWM [1]-[11] or resonant [12]-[18]. In such applications, if multilevel topologies are not used then expensive 1000-1200V devices would have to be used as the converter devices. With multilevel converters, cheaper devices with voltage ratings of 500-600V, greater availability and better switching characteristics can be used, but there has been little investigation of whether multilevel converters can be used in conventional DC bus voltage applications with a 400V DC bus.

Given that multilevel converters allow for cheaper, more available devices with better switching characteristics (less $R_{DS-ON}$ and $C_{oss}$, faster turn-on and turn-off) than devices for two-level converters to be used in high voltage applications, it seems possible that these advantages can apply to applications with conventional bus voltages. For example, in a 400 V DC bus application, devices with 250 V rating can be used instead of 500 V rating. Fairchild offers two MOSFET switches with almost the same drain current rating with 250V (FQD16N25CTM) and 500V (FDP18N50) voltage rating with the typical retail price of the 250V device being half that of the 500 V device [19]-[20]. Moreover, turn-on losses that are dependent on $C_{oss}V^2_{DC-bus}$ can naturally be reduced by 75% without using any auxiliary circuits or ZVS methods because the devices see just half the DC bus voltage at the time of turn-on instead of the full voltage.

Although multilevel converters for conventional DC bus applications with 400 V DC bus voltage seem a promising option, it does not seem to have been investigated. One reason might be that most power supply designers are not familiar with high voltage applications where multilevel converters are used and people who are familiar with these converters do not work on switch-mode power supplies. Another reason may be the perception that multilevel converters are complicated and expensive, but a three-level converter is just like a standard half-bridge or full-bridge converter with a couple of extra clamping diodes. Given the potential benefits of three-level converters described above, if converter efficiency can actually be improved by using three-level instead of two-level converters, then the cost of the extra diodes would be less than auxiliary circuits typically used to improve efficiency, (i.e. active snubbers [21]-[23]), and offset by the cost reduction in the converter switches.

There does not seem to be any obvious performance or cost reason why three-level converters cannot be considered for applications with DC bus voltages of 400 V. The main objective of this work is, therefore, to perform such an investigation and compare the operation of a three-level converter to a conventional two-level converter of the same type to see whether it makes sense to do so. For this investigation, the three-level series resonant converter shown in Fig. 1(a) will be used as the reference topology and it was chosen as (i) it is a resonant topology and resonant topologies have become increasing popular recently, and (ii) because it is the simplest resonant topology as opposed to series-parallel resonant or LLC resonant topologies. It was desired to focus on the characteristics of the three-level topology rather than on the complexities of a resonant topology. Note that the features of the converter to those of a two level converter shown n Fig. 1(b).

This paper reviews the operation of the converter and design considerations for the implementation of a prototype. Experimental results above, below and at the resonant frequency are presented and compared to each other. These results are also compared to similar results obtained from a two-level full-bridge converter. Conclusions are made at the end of the paper.

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The authors would like to acknowledge support from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

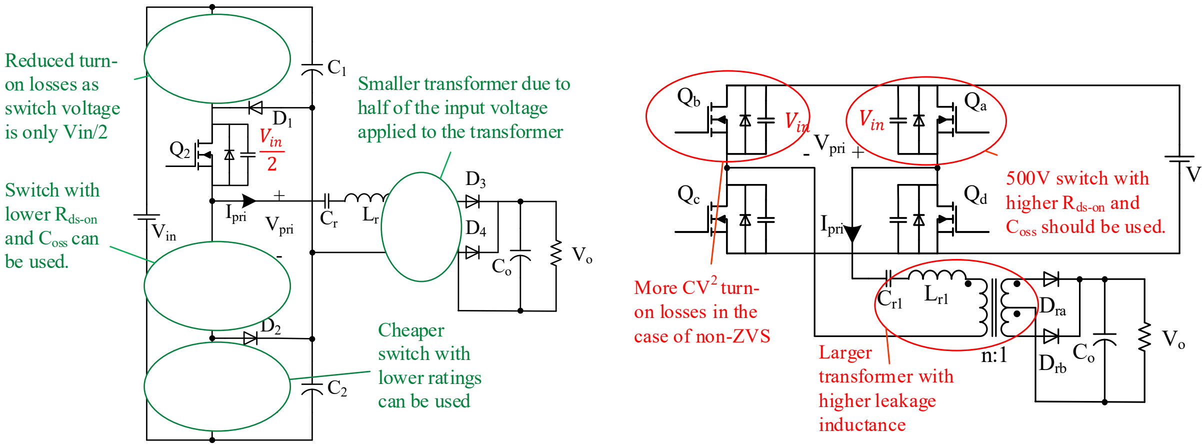


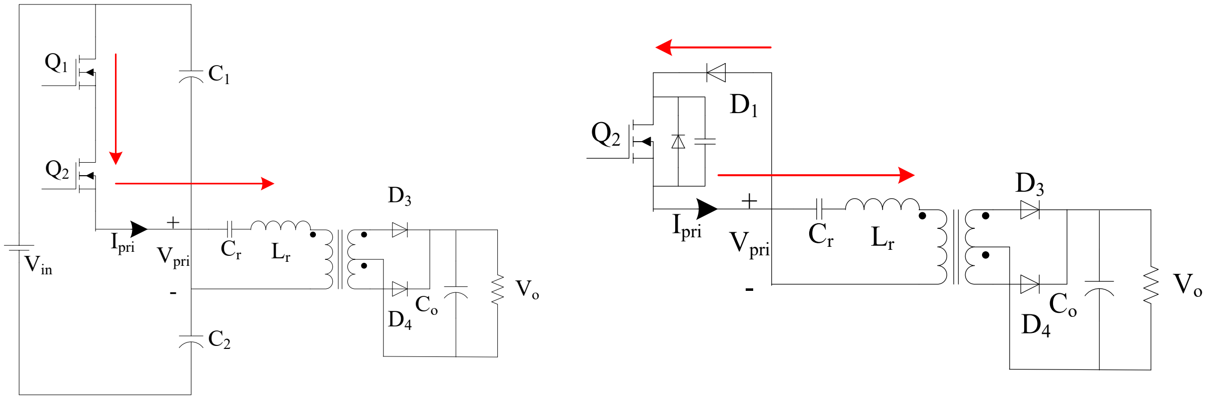
Fig. 1. Series-resonant DC-DC converter: (a)Three-level, (b) Two-level

## II. STEADY-STATE OPERATION PRINCIPLES

The basic operation of the converter in Fig. 1(a) is as follows: When $Q_1$ and $Q_2$ or $Q_3$ and $Q_4$ are on, then either the input voltage $V_{in}$ or 0 V appears at one end of the series resonant tank. Since the other end of the tank is connected to the midpoint of $C_1$ and $C_2$, it will always have $V_{in}/2$ volts. When $Q_1$ and $Q_2$ are on, then + $V_{in}/2$ volts is impressed across the resonant tank; when $Q_3$ and $Q_4$ are on, then - $V_{in}/2$ volts is impressed across the resonant tank. Zero voltage states can be impressed on the resonant tank if only $Q_2$ or $Q_3$ are on. A typical switching sequence for a switching cycle is therefore having $Q_1$ and $Q_2$ on, then just $Q_2$ on, then $Q_3$ and $Q_4$ on, then just $Q_3$ on until the start of the next switching cycle; Fig. 2 shows the first two intervals of this sequence. As a result of this sequence, a square wave with positive and negative polarity can be impressed across the resonant tank and the converter can operate in a manner similar to that of conventional two-level series resonant DC-DC converters. Voltage regulation can be performed either by operating the converter with fixed switching frequency and adjusting the width of the zero voltage states across the resonant tank or by neglecting the zero voltage states and using variable switching frequency control or by a combination of the two.

### *A. ZVS operation*

For ZVS operation, the switching frequency $f_{sw}$ must be greater than the resonant frequency of the $C_r$-$L_r$ tank $f_o$. Key modes of ZVS operation and typical converter waveforms are shown in Fig. 3. Fig. 3(a) shows the equivalent circuit for Mode 1 operation ($t_0 < t < t_1$) and Fig. 3(b) shows he equivalent circuit for Mode 2 operation ($t_1 < t < t_2$) and Fig. 3(c) shows the waveforms. Before the start of Mode 1 at $t = t_0$, the primary current is negative so that the anti-parallel diodes of $Q_1$ and $Q_2$ are conducting and $Q_1$ and $Q_2$ can be turned on with ZVS. It should be noted that the current is negative during a conduction angle of $\varphi$ and that the switches need to be turned on while current is flowing through the body diodes of $Q_1$ and $Q_2$ to ensure that $Q_1$ and $Q_2$ are turned on with ZVS. In this mode, a positive voltage is applied to the resonant tank, but the current is negative. Mode 2 starts at $t = t_1$ when the current through switches $Q_1$ and $Q_2$ becomes positive. The



(a) (b)

Fig. 2. (a) $Q_1$-$Q_2$ operation. (b) Zero voltage state mode with $Q_2$ on.

voltage across the tank continues to be positive until $Q_1$ and $Q_2$ are simultaneously turned off and current starts flowing through the body diodes of $Q_3$ and $Q_4$.

### *B. ZCS operation*

For ZCS operation, the switching frequency $f_{sw}$ is less than the resonant frequency of the $C_r$-$L_r$ tank $f_o$. ZCS can occur if the primary current leads the primary voltage as current can be extinguished in the converter switches before they are turned off. This is true if blocking diodes are placed in series with switches having body diodes or reverse blocking devices are used as the switches. It is also true if switches with body diodes are used, but in this case considerable current may flow through the body diodes, thus creating significant conduction losses. If the primary current is small, however, then the resonant tank can be designed so that the primary current is discontinuous with a resonant hump. This is the approach that has been taken in this paper given that the power levels under consideration are moderate.

Key modes of ZCS operation and waveforms are shown in Fig. 4. Fig. 4(a) shows the equivalent circuit for Mode 1 operation ($t_0 < t < t_1$) and Fig. 4(b) shows he equivalent circuit for Mode 2 operation ($t_1 < t < t_2$) and Fig. 4(c) shows the waveforms. At the start of Mode 1, switches $Q_1$ and $Q_2$ are on, a voltage of $+ V_{in} / 2$ is applied to resonant tank and current begins to flow in the primary. It should be noted that $Q_1$ and $Q_2$ are turned on with ZCS as primary current was extinguished sometime during the previous half switching cycle when $Q_3$ and $Q_4$ were on. Due to the resonant tank, the primary current is forced to rise then eventually fall to zero and Mode 2 begins. During Mode 2, the primary current remains at zero and the output capacitor supplies the load. $Q_1$ and $Q_2$ can be turned off with ZCS sometime during Mode 2.

### *C. Resonant frequency operation*

When the converter is working with unity power factor operation with the primary current and voltage in phase, its operation is the same as for ZCS operation except that the zero current conduction angle $\lambda$ is zero and the primary current is purely sinusoidal.

## III. DESIGN CONSIDERATIONS

The converter shown in Fig. 1 can be designed to operate in three different ways:

### *A. ZVS operation mode*

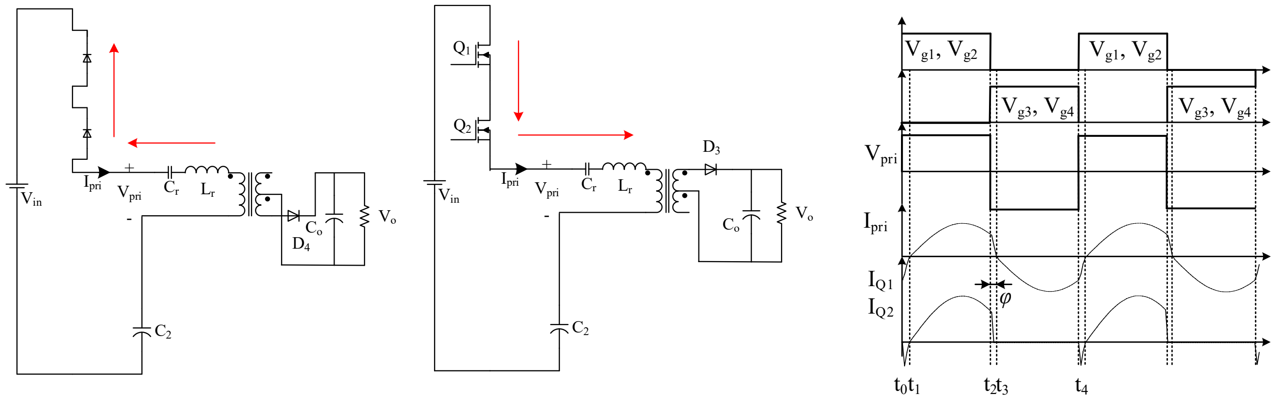
The amount of phase shift between the primary voltage and current, $\varphi$, which determines how much the resonant converter current lags the voltage, is an important part of the resonant converter design procedure. A current with low lagging $\varphi$, causes the converter switches to operate with partial ZVS so that switching losses increase. Switching losses become more significant for heavier loads and converter efficiency decreases.

On the other hand, a current with high lagging $\varphi$ ensures the ZVS operation of the converter switches over a wide range of load variations as this creates additional circulating current in the converter primary side. This extra current causes more conduction losses in the switches of the converter. These losses become more important under light load operation conditions and thus light-load efficiency will be affected.

The above-mentioned problems are not as serious in multilevel converters as they are two-level converters. In the case of three-level converters, the switches block half of the bus voltage so that a maximum of one-quarter of the energy that is stored in the output capacitance of a switch in a two-level converter is stored in the output capacitance of a switch in a three-level converter. Less energy means less lagging current is required to discharge the parasitic capacitors of the converter switches. If the lagging current is insufficient to fully discharge the output capacitance of the converter switches, the switching losses in the three-level converter are not as much as the switching losses in the two-level converters. This fact can be used in some applications to improve the efficiency characteristic of a resonant converter operating under light-load conditions.

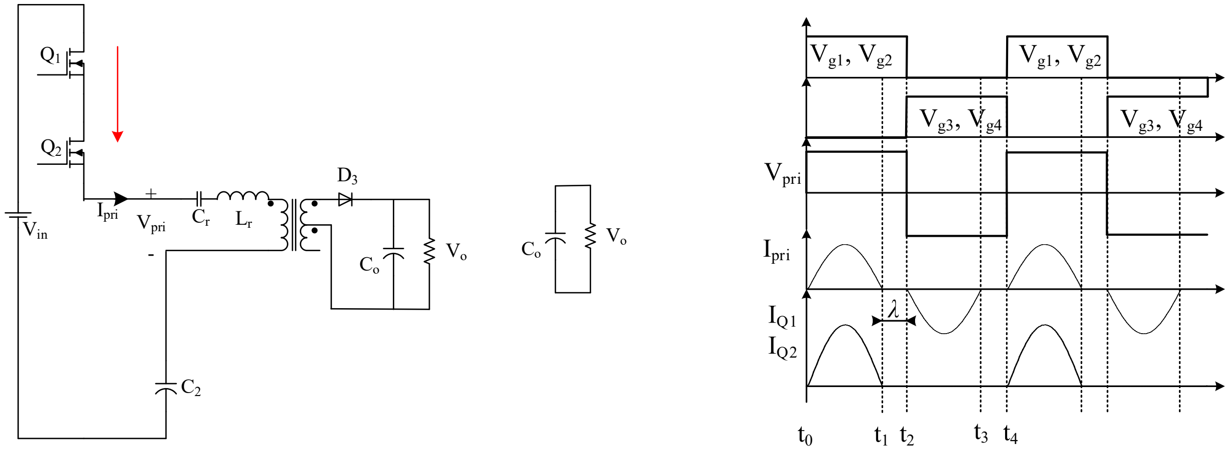
### *B. ZCS operation mode*

If the primary current is small, then the tank can be



(a) (b) (c)

Fig. 3. ZVS operation (a) Mode 1 ($t_0 < t < t_1$) (b) Mode 2 ($t_1 < t < t_2$) (c) Typical converter waveforms.



(a) (b) (c)

Fig. 4. ZCS operation (a) Mode 1 ($t_0 < t < t_1$) (b) Mode 2 ($t_1 < t < t_2$) (c) Typical converter waveforms.

designed so that the primary current is discontinuous with a resonant hump. This is what was done for this paper as the power levels under consideration are moderate. When the output power increases, the primary current peak value will increase. The higher peak value means more RMS current flows in the converter primary, but average current does not increase as much. More RMS current leads to higher conduction losses in the converter primary and the overall efficiency of the converter will decrease. This feature can be used by power electronic designers to modify the efficiency characteristic of three-level resonant converters in some applications.

### C. *Resonant frequency operation mode*

The converter's switching frequency can be made to be at the resonant frequency and the primary current is made to be in phase with the voltage across the resonant network. As there is no leading or lagging current, this case represents the case when there is a minimum amount of circulating current and peak current.

In this mode of operation, the converter primary current is ideally zero during the switching transition and switching losses are zero; also, the lagging and leading components of the current is zero and converter conduction losses are minimal. The efficiency of a three-level resonant converter designed to work in this mode is also less dependent on parameter variations because ZVS can be achieved more easily than in two level converters.

Given that the switches in a three-level converter are exposed to only half the DC bus voltage as those of a two-level converter, they will automatically have less $CV^2$ related turn-on losses. In fact, the reduction can be as much as 75% and this is without using any active snubbers of any kind. Since a three-level converter is based on the conventional half-bridge topology, however, it will have twice the current flowing in its primary than will a two-level converter and thus is susceptible to higher conduction losses. Under very heavy load conditions, a two-level full-bridge converter is more efficient than a three-level conditions as current related losses dominate, but a three-level converter is more efficient than a two-level converter under light load conditions where current related losses are less dominant than turn-on switching losses.

The approach used to study the operation of a three-level converter with reduced DC bus voltage was as follows:

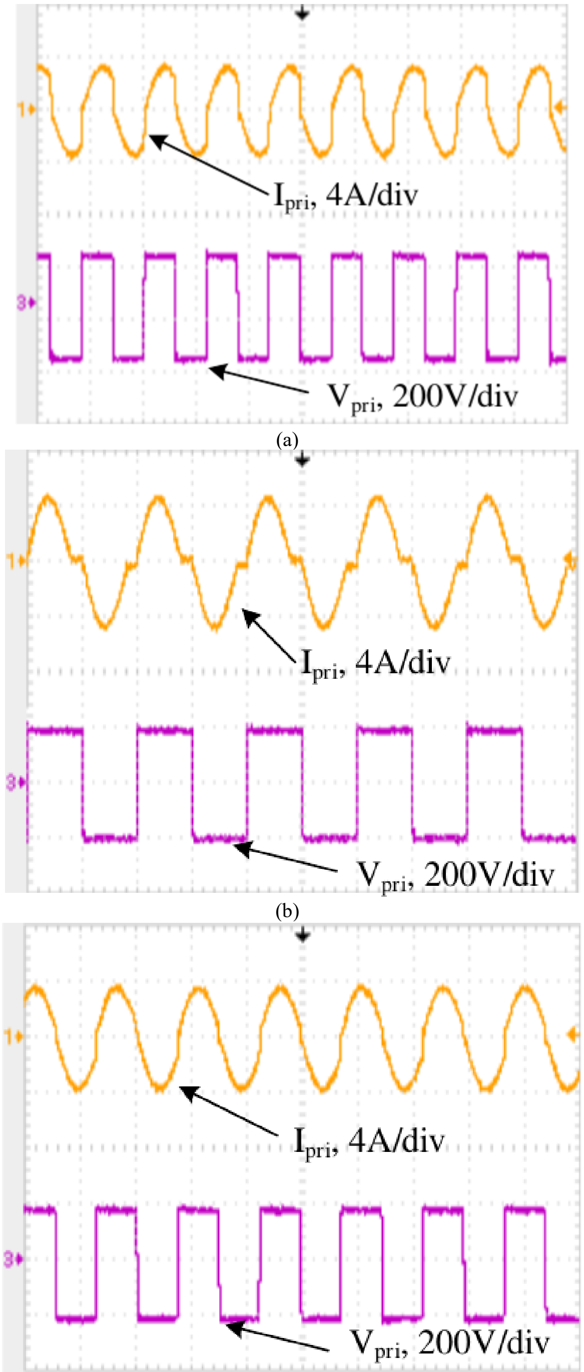
(i) A three-level converter was designed to operate with ZVS operation, ZCS operation and resonant frequency operation with a 400 Vdc bus. The design was done keeping in mind that $CV^2$ are naturally reduced by 75% so that there was less need to ensure that the switch output capacitances were discharged before switch turn-on to ensure ZVS operation.

(ii) The converter was operated with a fixed switching frequency for all three cases, but with a different switching frequency. In other words, ZVS operation was done at one switching frequency and the converter's duty cycle was adjusted to regulate the load, ZCS operation was done at another fixed switching frequency and resonant frequency operation was done at yet another switching frequency.

## IV. EXPERIMENTAL RESULTS

A simple proof-of-concept prototype of the series-resonant three-level DC-DC converter shown in Fig. 1(a) was built according to the following specifications: Input voltage Vin =400V, output voltage $V_o$ = 48 V, maximum output power $P_{o,max}$ = 500W, resonant frequency, $f_o$ = 68 kHz. The devices used for switches $Q_1$-$Q_4$ were FDP51N25 MOSFETs, BYV29 diodes were used for primary side diodes $D_1$-$D_2$ and STPS20H100CT devices were used for the output rectifying diodes. The resonant tank values were $C_r$=220 nF, and $L_r$=28.3 μH and the transformer turns ratio was 4:1.

Fig. 5 shows the converter's primary voltage and current typical waveforms for the three different types of operation described in the previous section. The converter was operated



(a)

(b)

(c)

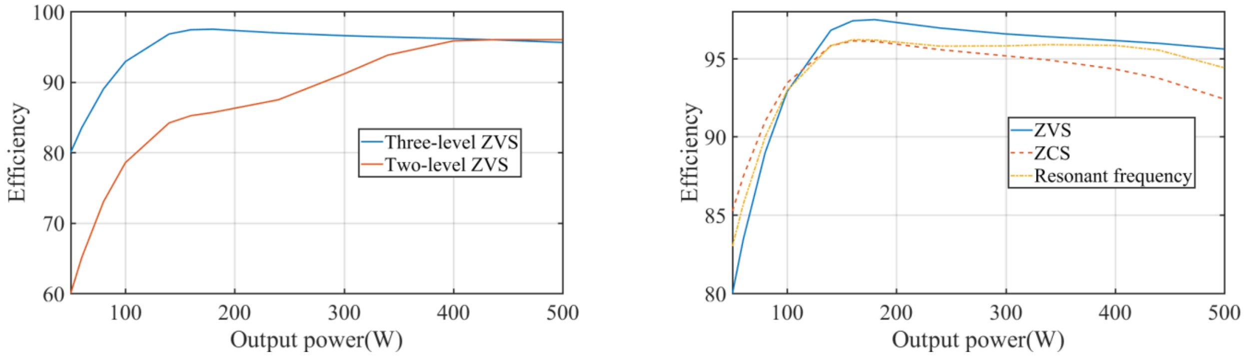
Fig. 5. Typical converter waveforms: (a) Primary voltage and current fsw= 85kHz, fsw>fo (t: 10 µs/div.), (b) Primary voltage and current fsw= 50kHz, fsw<fo (t:10 µs/div.), (c) Primary voltage and current fsw= 68kHz, fsw=fo (t: 10 µs/div.)

with a combination of variable and fixed switching frequency as described in the previous section. Fig. 5(a) shows the waveforms when the converter is operating in ZVS operation mode with $f_{sw}$ = 85 kHz. Fig. 5(b) shows the waveforms when the converter is operating in ZCS operation mode with $f_{sw}$ = 50kHz. Fig. 5(c) shows the waveforms when converter when the converter is operating at the resonant frequency $f_{sw}$= 68 kHz. From Fig. 5, it can be seen that the primary current lags the primary voltage for ZVS operation in Fig. 5(a), that the primary current is a resonant hump and that ZCS can be achieved in Fig. 5(b) and that primary current and voltage are in phase in Fig. 5(c).

In order to compare the efficiency of resonant converters for a three-level converter to a two-level converter, a prototype of a conventional two-level full-bridge series-resonant converter was built. The two-level converter prototypes had a resonant frequency of $f_o$ = 58 kHz. The two-level full-bridge converter was operated with lower switching frequency than the three-level converter because its transformer was larger with more primary windings and thus more leakage inductance, which impacted the design of the resonant tank so that the resonant frequency became lower. The devices used for switches in the two-level full bridge converter were FDP18N50 MOSFETs, and STPS20H100CT devices were used for the output rectifying diodes. The resonant tank values were $C_{r1}$=100 nF, and $L_{r1}$=77 µH and the transformer turns ratio was 8:1. Fig. 6(a) shows a graph of efficiency vs load for both three-level and two-level converters operating with ZVS. It can be seen that the three-level converter is the more efficient converter for the load range under study. This is especially true when the converters are operating with light loads, mainly because neither converter is operating with ZVS under light-load conditions, but the three-level converter switches have fewer $CV^2$ losses as their switches are exposed to half the DC bus voltage before turn-on.

Fig. 6(b) shows a graph of the efficiency for the three-level converter for ZVS, ZCS and resonant frequency operation. It can be seen that ZVS operation is the most efficient when the converter is operating above 100 W, even though it is operating with a higher switching frequency. ZCS operation is the most efficient under light-load conditions (≤ 100 W). These efficiency results can be explained as follows: Since the converter switches are exposed to $V_{in}/2$ voltage and Vin is not very high (400 V), the turn-on losses of the MOSFETs are inherently reduced by a significant amount. For light-load operation, both ZVS and ZCS converters do not have ZVS, but the ZCS converter operates with ZCS so that ZCS operation results in fewer net losses. Moreover, ZCS operation occurs at lower switching frequencies than ZVS and is also a factor in light-load efficiency. For heavy-load operation, the ZVS converter operates with ZVS and the primary current is distorted with a larger peak and with more harmonics when ZCS operation is used. As a result, ZVS operation results in fewer net losses.

It should be noted that the volt-seconds of the transformer when the ZCS converter is operating with light-load at ≤ 100 W are less than the volt-seconds of the transformer when the ZVS converter is operating at 85 kHz. This means that the three-level converter can be operated with ZCS and lower switching frequency at light loads and thus with greater efficiency without the transformer saturating – that 50 kHz light load operation is possible with an 85 kHz transformer. The lower volts-seconds is due to the reduction in duty-cycle of the converter switches under light-load conditions.



(a) (b)

Fig. 6. Converters efficiency vs output power: (a) Three-level and two-level converter operating with ZVS (b) Three-level converter operation with ZVS, ZCS and resonant frequency.

## V. CONCLUSION

Multilevel DC-DC converters are used in applications with high DC bus voltages so that cheaper, more available devices with better switching characteristics. There does not seem to be a good, obvious reason why the same cannot be true for applications with conventional DC bus voltages like 400 V, and it was the purpose of this investigation to actually make the comparison. Three-level and two-level series-resonant converters were chosen as the test topologies. It was determined that:

- The three-level converter was more efficient than the two-level converter for the load range under study, especially under light-load conditions, due to the reduction of $CV^2$ losses, even though it was operated at higher switching frequency.
- The converter can be made to operate with a lower switching frequency and with ZCS instead of ZVS under light-load conditions, to improve light-load efficiency. A 85 kHz transformer will not be saturated in a converter working with 50 kHz frequency at light load.

## ACKNOWLEDGMENT

The authors would like to acknowledge support from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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