Variable Frequency Multiplier Technique for High Efficiency Conversion Over a Wide Operating Range

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Abstract
This paper presents a variable frequency multiplier technique (VFX) that enables design of converters for wide input and/or output voltage ranges while preserving high efficiency. The technique is applied to an LLC converter to demonstrate the effectiveness of this technique for converters having wide input voltage variation such as universal input power supplies. This technique compresses the effective operating range required of a resonant converter by switching the inverter and/or rectifier operation between processing energy at a fundamental frequency and one or more harmonic frequencies. The implemented converter operates over an input voltage range of 85 V to 340 V but the resonant tank and conversion ratio has only been designed for half this range and VFX mode of the inverter is used to enhance this to the full range. Experimental results from a 50 W converter show an efficiency of 94.9% to 96.6% across the entire input voltage range, demonstrating the advantage of using this technique in such applications.

Introduction
A trend in power electronics has been to strive for high power density and efficiency across over a wide operation range [1]. High power density can be achieved by switching the converter at a high frequency. At these high frequencies, resonant converters use soft switching (i.e. Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS)) to reduce the overlap of current and voltage during switching transitions to achieve high efficiency [2], [3]. Although soft-switched resonant converters can achieve high efficiency at nominal operation, the efficiency tends to degrade considerably with variation in input voltage, output voltage and power level [4].

Resonant converters commonly use frequency control [2], [3] and/or phase shift control [5], [6] to compensate for variation in voltage and power levels. If switching frequency is increased to reduce power or gain of the converter, such as in Series Resonant Converters operated above resonance for ZVS, switching losses will increase. Also, with a wide frequency range the magnetics cannot be optimally designed. Furthermore, circulating currents may increase resulting in higher loss at light loads. With phase shift control operation over a wide range is likewise challenging. The two legs of the inverters are phase shifted with respect to each other and thus have asymmetrical current levels at the switching transitions. The inverter leg in which current is leading the voltage can lose ZCS and the leg in which current is lagging can lose ZVS. Other control techniques such as asymmetrical current mode control [7] and asymmetrical duty cycle PWM control [8] also have limitations such as loss of ZVS.

In this paper, a Variable Frequency Multiplier (VFX) technique is introduced and its effectiveness is demonstrated for a universal input power supply. In the VFX technique, additional "frequency multiplier" modes of operation of the inverter and/or rectifier are used to provide additional sets of operating characteristics for the converter to achieve and maintain high performance across a wide operating range. Frequency multiplier circuits are often used in extreme high-frequency RF applications (e.g., where transistor $f_T$ is a concern), and are sometimes used in switched-mode inverters and power amplifiers (e.g., [9], [10]). While it has been proposed to employ frequency multipliers in dc-dc converters (e.g., [11], [12]), this is not usually done, as the output power of a frequency multiplier inverter is inherently low relative to the needed device ratings. However, here we propose use frequency multiplication as an additional operating mode of the inverter rectifier, for wide-range voltage and/or power conditions. In this context, frequency multiplication can be used to extend the efficient operating range of a converter and improve its performance across power and voltage.

While the proposed VFX technique can be applied to the inverter and/or rectifier and for wide input and/or output range, here we demonstrate it for wide input voltage range using VFX of the inverter. Universal input power supplies need to operate over a wide input voltage range and it is a challenge to design resonant power converters for such wide range of operation. In this paper we demonstrate the VFX technique in the inverter of LLC converter to achieve efficient operation across an input voltage range from 85-340 V.
In section II, the variable frequency multiplier technique is introduced and discussed, in section III the design and analysis of an LLC converter operating in the two modes is presented, experimental results are presented in section IV, and the last section concludes the paper.

**Variable Frequency Multiplier Technique**

The Variable Frequency Multiplier (VFX) technique can be applied to the inverter stage and/or rectifier stage to achieve wide input voltage and/or output voltage range operation. In this technique, the duty ratio and switching frequency of an inverter or rectifier in the converter may be changed such that it processes power between dc and a harmonic of its switching frequency (rather than just its fundamental) to create different modes of operation. By operating between dc and a harmonic, the dc-ac (or ac-dc) voltage gain of the inverter or rectifier changes, and one gains an added operating mode with different transfer characteristics. This allows the converter to be operated over a narrower (intermediate ac) frequency range for a wide voltage conversion range and/or power range. Depending on the circuit architecture, more than two modes can be created; the full paper will present a general set of tradeoffs and conditions for VFX operation in different modes. As an example, in this paper a two mode VFX converter with VFX technique applied to the inverter stage is demonstrated.

To explain the working of the VFX technique applied to an inverter a stacked bridge inverter is used as shown in Fig. 1. This inverter operates in two modes, mode 1 (fundamental mode) and mode 2 (second harmonic VFX mode). In mode 1, there are two switching states in one switching period. In state A switches 1 and 4 are on and in state B switches 2 and 3 are on as shown in Fig. 2.

![Figure 1: Stacked bridge inverter with input voltage $V_{in}$ and output voltage $V_{inv}$.](image1)

![Figure 2: Stacked bridge inverter with input voltage $V_{in}$ and output voltage $V_{inv}$ in mode 1; in (a) state A and (b) state B](image2)
In mode 2, there are four switching states in one switching period. In state A switches 1 and 3 are on, in state B switches 2 and 3 are on, in state C switches 2 and 4 are on and in state D switches 2 and 3 are on as shown in Fig. 3. The VFX mode results in double the output frequency for a single switching cycle. Thus for the transformation stage to see the same frequency as in mode 1 this mode is operated at half the switching frequency.

Figure 3: Stacked bridge inverter with input voltage $V_{\text{in}}$ and output voltage $V_{\text{inv}}$ in mode 2; (a) state A and (b) state B, (c) state C, (d) and state D

To extend this to other topologies, frequency analysis is useful. Each half bridge outputs a square wave voltage which can be expressed as a Fourier series in Equation 1. In mode 1, the duty ratios are identical ($D_1 = D_2 = 0.5$) and 180 degrees out of phase so the fundamental of the half bridge waveforms reinforce. In mode 2, $D_1 = 0.25$ and $D_2=0.75$ as shown in Fig. 4. In this mode the fundamental of the half bridge waveforms is canceled while the second harmonic is reinforced so the output frequency doubles. Hence, different modes can be created by selecting different duty ratios and time delays between half bridges.
Figure 4: Output voltages of the two inverters $v_{inv1}$ and $v_{inv2}$ in Mode 2

$$v_{inv1} = D_1 V_{in} + \sum_{i=1}^{\infty} \frac{2V_{in}}{\pi n} \sin \left( \frac{n \pi D_1}{T} \right)$$

**Design of the LLC converter with vfx technique**

We demonstrate the proposed technique in a dc-dc converter designed for a two-stage universal laptop power supply. The AC voltage input varies in different countries but the nominal voltage is either 110-120 Vrms at 60Hz, or 220-240 Vrms at 50 Hz. Thus 120 V and 240 Vrms has been selected as the maximum voltages, corresponding to a peak input voltage of 170 V and 340 V applied to the dc-dc converter depending upon country. The variable frequency multiplier technique is very useful for this because there are two distinct modes of operation.

An LLC converter has been selected for the dc/dc stage. It uses frequency control to regulate the output voltage and has many advantages. The main advantages are that it has the capability to regulate the output voltage over a wide range of input voltage and power with only a small variation in the switching frequency [13]. Also, it achieves Zero Voltage Switching (ZVS) over the entire range of operation thus reducing the switching losses. Moreover, the leakage and magnetizing inductance of the transformer can be incorporated into the design.

Figure 5 shows the schematic for the LLC converter with VFX inverter operation. As it has very high input voltage, stacked half bridges are used. This reduces the voltage stress of the transistors by half which increases their performance with available devices. The transformation stage consists of a series inductor ($L_r$) and a capacitor ($C_r$) and a parallel inductor ($L_m$). The capacitor not only provides resonant filtering but also provides dc blocking for flux balancing.

Figure 5: Schematic of the LLC converter with a stacked bridge inverter incorporating the VFX technique.
The transformer parasitics, leakage and magnetizing, can be used instead of individual discrete inductors [14]. A center tapped transformer is used to reduce the number of rectification diodes. This increases the loss of the transformer and the voltage stress of the diodes. However, this trade off is still beneficial because of the low output voltage. Synchronous rectification can be used to reduce the power loss of the diodes [15], [16], [17].

The full design of the converter system will be treated in the full paper, but we summarize the approach here. The converter is designed using the method outlined in [18]. Fundamental harmonic analysis has been used to analyze and design the converter. Time-based [19] and approximate methods [20], [21] can be used for more accurate gain analysis.

The converter is designed for maximum voltage input of 170 V in "fundamental mode" and an output voltage of 20 V. To ensure sufficient power factor greater than 0.95, the minimum input voltage for the dc-dc stage is 85 V. For input voltages above 170 V, VFX mode is used to decrease the voltage that the transformation stage sees by half. The transformer ratio has been selected as

$$n = \frac{V_{in-max}}{2V_{out}} = 4.25$$

The ratio of \( L_m/L_r \) (referred to as \( k \), in the text) is chosen as 7. The maximum gain is selected as 2.4, a little higher than 2, to ensure that even with the inaccuracies due to the fundamental harmonic analysis the converter still behaves as required. To ensure ZVS is maintained even with maximum load at minimum input voltage the maximum value of \( Q = \sqrt{L/C}/R_n \) is calculated. This is found by equating the imaginary part of the impedance looking out of the inverter as zero. \( Q_{max} \) is calculated as

$$Q_{max} = \frac{1}{k} \sqrt{\frac{1 + \frac{1}{k(1 - R_{out})}}{R_{out}}} = 0.1706$$

Where \( R_n = 8V_n^2n^2/(\pi^2P) \) and \( n \) is transformer turns ratio and \( P_{out} \) is the output power. The values of \( n, k, R_n \) and \( Q_{max} \) are used to calculate \( L_r, L_m \) and \( C_r \). Where \( L_r = \frac{Q_{max} R_n}{w} = 6.36 \mu H \), \( L_m = k L_r = 44.5 \mu H \) and \( C_r = \frac{1}{Q_{max} R_n w} = 15.9 \mu F \) and the dead time is calculated as \( t_d = 8C_{ds} f_s L_m = 62 \) ns.

![Figure 6: The gain of the transformation stage with peak gain at 0.4 times the normalized resonant tank \((L_r \text{ and } C_r)\) frequency.](image)

![Figure 7: Picture the (a) top side and (b) bottom side of the prototype board.](image)
Using fundamental harmonic analysis the gain curve of the transformation stage is given in Fig. 6. If the converter had not been designed considering the VFX mode, double the gain and transformer turns ratio would be needed to operate over the entire range, thus increasing the total loss.

Experimental Prototype and Results

Figure 8: Current and voltage waveforms of the converter when operated in mode 1, fundamental mode, at input voltage of (a) 170 V and (b) 85 V and when operated in mode 2, VFX mode, at input voltage of (c) 170 V and (d) 340 V. (1-Blue) Gate voltage of switch $S_1$, (2-Turquoise) drain-source voltage of switch $S_4$, and (4-Green) current output of lower half-bridge that is flowing in to the transformer primary.
Figure 9: Efficiency of the converter with variation in (a) input voltage with fixed output voltage and 50 W output power and with variation in (b) output power with 170 V input voltage and fixed output voltage.

Using the design values from the previous section, a prototype for the converter was built as shown in Fig. 7. The dc/dc converter is a step-down converter operating at the series tank \((L_s, C_r)\) resonant switching frequency of 500 kHz. It has an input voltage range of 85 V - 340 V, fixed output voltage of 20 V and an rated output power of 50 W. To control the output power and the gain, frequency control is utilized, while the VFX operating mode is changed based on input voltage. The transformer was designed to exploit the integrated magnetizing inductance. The leakage inductance was used as the resonant inductance. However, this was insufficient and series inductor was added to provide the required resonant inductance.

The converter operates with ZVS across the entire range of operation. The switching waveforms for input voltages of 170 V and 85 V in the normal mode are given in Fig. 8 (a) and (b), respectively. It shows the current input to the transformer primary which is also the output current of the bottom inverter, the gate drive voltage of switch \(S_4\) and the \(V_{ds}\) of switch \(S_4\). For above 170 V, mode change occurs and the waveforms for 170 V and 340 V are give in Fig. 8 (c) and (d), respectively. The converter is operated at half the normal mode switching frequency and even in this mode we achieve ZVS and thus high efficiency. The efficiency of the converter was measured across variation in the input voltage in both the modes and across output power. The measured efficiency of the converter as a function of input voltage is plotted in Fig. 9 (a). The converter continues to operate with high efficiency with the mode change and converter efficiency varies from 94.9% to 96.6% across the entire
range of input voltages. The measured efficiency as function of output power and fixed input voltage of 170 V varies from 86% to 95.4% and is plotted in Fig. 9(b). The full paper will provide a more detailed set of experimental results showing the efficacy of VFX operation.

**Conclusion**

This paper presents Variable Frequency Multiplier technique for resonant power converters. The approach is applied to an LLC converter, to demonstrate the effectiveness of this technique for universal input power supplies. This technique increases the input voltage range by a factor of two and the converter achieves high efficiency over a wide range of operation. The experimental prototype is able to achieve an efficiency of 94.9% to 96.6% across the entire input voltage range at 50 W output power and 86% to 95.4% across the entire power range with 170 V input voltage. Hence, the VFX technique can be very useful to obtain high efficiency across a wide range of operation. The full paper will provide much more detail about the operation, design and control of dc-dc converters with variable frequency multiplication.

**Appendix**