Distributed Sinusoidal Resonant Converter with High Step-Down Ratio

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***Abstract*—A novel zero-current switching transformer-based sinusoidal resonant converter topology for point-of-load DC-DC conversion is presented in this paper. A sinusoidal resonant converter within a distributed power system, where high step-down ratios are required, is challenging due to the large parasitic impedance seen by the primary stage. A sinusoidal resonant converter with a distributed topology is introduced here to reduce the transformer turns ratio while maintaining a high step-down ratio. A power efficiency of 89.8% is achieved. The proposed distributed converter is highly scalable and exhibits sinusoidal current and voltage waveforms with low current spikes. Application to systems-in-package, wireless devices, and IoT is expected due to the low EMI and high efficiency characteristics of this distributed converter system.**

***Index Terms*—Resonant converter, high step-down ratio DC-DC converter, distributed topology, electromagnetic interference.**

I. Introduction

COMPACT systems-in-package and three-dimensional (3-D) integrated circuits (ICs) exhibiting small form factors are primary platforms for modern applications, such as portable devices and the internet of things (IoT). Smaller passive elements along with a fast transient response require on-chip or in-package power conversion systems to operate at high frequencies [1], [2]. A conventional switching power converter, for instance, a pulse width modulation (PWM) converter, suffers however from switching losses at high frequencies, limiting utilization in modern high performance applications [3]. Due to zero-current switching (ZCS) and zero-voltage switching (ZVS) properties, resonant converters are considered an alternative to PWM converters [3]. The waveform of the current flowing through the converter affects the generated electromagnetic interference (EMI), where the harmonic distortion associated with the high frequency current increases EMI [4], [5]. A resonant converter with a quasi-sinusoidal current waveform therefore exhibits fewer harmonics (ideally only the fundamental component), significantly mitigating EMI.

Due to the lower distribution losses, a distributed power architecture (DPA) has become a widely used power distribution topology [6], [7]. In DPA systems, an AC voltage is converted to a medium level DC voltage (for example, 55 volts). The medium level DC voltage is subsequently converted to an on-chip voltage level using local PoL converters. With on-chip voltage scaling to 0.8 volts and lower voltages, high step-down ratio converters for DPA systems reduce transmission losses while providing high efficiency [6]. Although directly increasing the turns ratio of a transformer can achieve high step-down ratio conversion, the power efficiency would be degraded due to the significant parasitic impedances. A distributed sinusoidal resonant converter where each transformer exhibits a low turns ratio is therefore proposed here. A high step-down ratio and high power efficiency are achieved while maintaining low EMI.

The rest of the paper is organized as follows. The operation and performance characteristics of a sinusoidal resonant converter are described in Section II. The performance degradation of the sinusoidal resonant converter caused by the high turns ratio is discussed in Section III. In Section IV, a novel distributed sinusoidal resonant converter is introduced. The performance and power efficiency of this converter are also presented. Some conclusions are offered in Section V.

II. Point-of-load sinusoidal resonant converter

A sinusoidal resonant converter consists of four parts: (1) a primary stage *LC* tank, (2) a transformer, (3) a rectifier in the secondary stage, and (4) an *LC* filter, as illustrated in Figure 1. A full wave rectifier in the secondary stage of the converter transforms the AC current from the transformer into a DC current flowing to the load. Switches within the resonant converter are based on power MOSFETs, as illustrated in Figure 1. An *LC* filter removes any high frequency harmonics originating from an imperfect sinusoidal current as well as stabilizes the output voltage.

The step-down transformer transfers the sinusoidal current from the primary stage (I_{res}) to the branches of the secondary stage ($I_{branch1/2}$). The magnitude of $I_{branch1/2}$ is determined from both the load and the turns ratio of the transformer. The

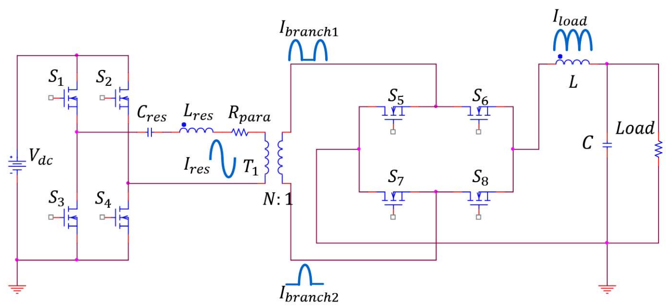

Fig. 1. Full bridge ZCS isolated quasi-sinusoidal resonant converter

This research is supported in part by the National Science Foundation under Grant Nos. CCF-1526466, and CCF-1329374, IARPA under Grant No. W911NF-14-C-0089, AIM Photonics under Award No. 059447-007, the Intel Collaborative Research Institute for Computational Intelligence (ICRI-CI), and by grants from Cisco Systems and Qualcomm.

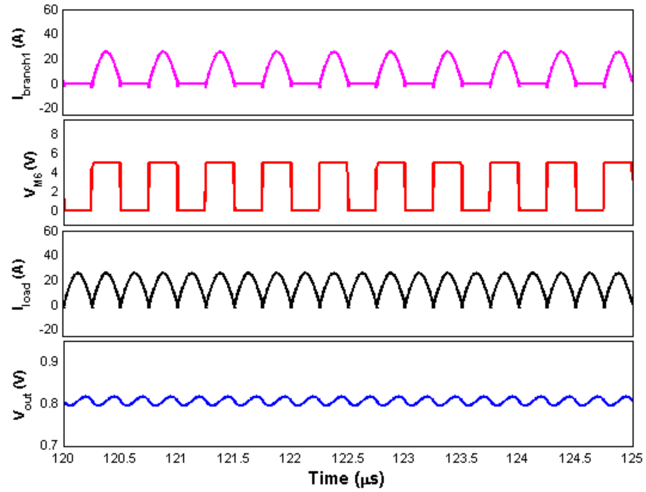

Fig. 2. Waveforms characterizing performance of the sinusoidal resonant converter

switch pairs, S_6 and S_7, and S_5 and S_8, are controlled to intermittently turn on and off at the resonant frequency of the primary *LC* tank stage. The load current I_{load} is therefore a positive half cycle sinusoidal current operating at twice the resonant frequency, as illustrated in Figure 1. Due to the output capacitor C_{out}, the voltage across the output load exhibits less ripple, proportional to the current flowing through the load.

A 12 volt DC input and a 0.8 volt DC output voltage, a typical voltage level in advanced CMOS technologies, is assumed [8]. An ideal transformer with a turns ratio of 15 achieves the step-down conversion. The load is modeled as a resistor. The magnitude of the load resistance is dependent on the current demand. A positive half cycle sinusoidal current I_{load} flows to the load, as illustrated in Figure 2. A medium step-down ratio conversion is achieved, where the output voltage is stable around 0.8 volts, and exhibits less than 4% ripple. A transient response of less than 1 μs to changes in the load is achieved with this topology.

III. Performance degradation due to high turns ratio

A transformer with a high turns ratio is required for high step-down ratio conversion in DPA systems. Two case studies with large input voltages and a high step-down ratio have been evaluated. The performance is compared to the converter described in Section II. 22 volts and 55 volts are used as input voltages in these two case studies. The output voltage in both

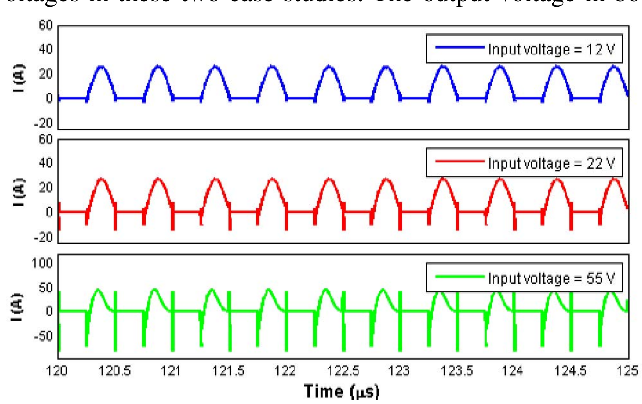

Fig. 3. Performance degradation of a high turns ratio converter

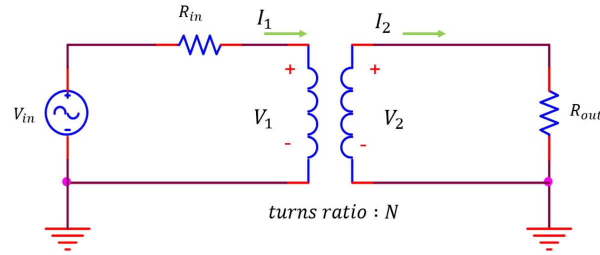

Fig. 4. Working principle of basic transformer

cases is 0.8 volts. Other circuit parameters such as the *LC* tank, parasitic impedance, switches, and load behavior are similar to the transformer described in Section II.

The current flowing through branch 1 $I_{branch1}$ in each of the converters is illustrated in Figure 3. Current spikes are observed in both cases when the branch current waveform crosses zero. The magnitude of the current spikes increases with a higher turns ratio of the transformer, as illustrated in Figure 3. In the case of the 55 volt input, the current waveform is significantly distorted, no longer maintaining a sinusoidal shape. Large current spikes of 90 amperes produces greater EMI, resulting in a less robust and noisy system.

The effect of the turns ratio of a transformer on the behavior of a converter is illustrated in Figure 4. An ideal transformer is assumed, where

$$\frac{V_1}{V_2} = \frac{I_2}{I_1}, \tag{1}$$

is maintained. The voltage across the primary winding is

$$V_1 = \frac{N^2 R_{out}}{N^2 R_{out} + R_{in}} V_{in}. \tag{2}$$

The current through the primary winding is

$$I_1 = \frac{V_{in}}{N^2 R_{out} + R_{in}}. \tag{3}$$

From (2) and (3), the parasitic impedance seen by the primary stage is N^2 times larger than the actual resistance. With increasing *N*, the effect of the parasitic impedance on the secondary stage grows exponentially, leading to a distorted current waveform within the *LC* tank. A sinusoidal resonant converter with a high turns ratio is therefore a challenging requirement. Nonetheless, a high step-down ratio is required for DPA PoL converters due to the high input and low on-chip output voltage levels. A converter with a small turns ratio transformer and high step-down ratio is therefore desired.

IV. High step-down ratio distributed sinusoidal resonant converter

To maintain high step-down ratio conversion, a scalable distributed topology for the sinusoidal resonant converter is proposed. As illustrated in Figure 5, a distributed topology is achieved by cascading multiple primary stages in parallel with multiple secondary stages. The secondary stage of each branch is connected to the load without contention from other branches. The secondary stage voltage of the distributed topology is similar to the voltage of a single branch sinusoidal

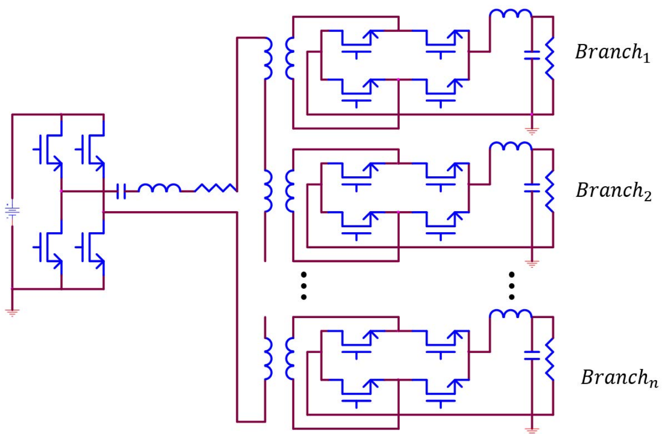

Fig. 5. Sinusoidal resonant converter with distributed topology

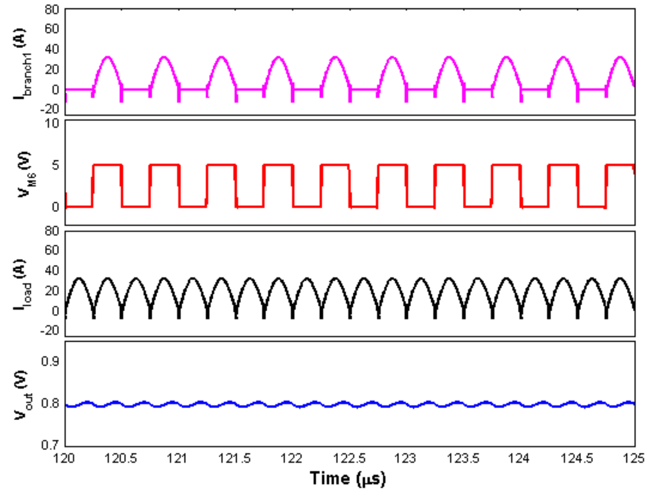

Fig. 6. Waveforms characterizing performance of distributed sinusoidal resonant converter

resonant converter. High step-down ratio conversion is therefore achieved using multiple transformers with a low turns ratio.

The topology of the distributed sinusoidal resonant converter is evaluated for high step-down ratio PoL conversion. The distributed topology consists of eight branches. Each branch exhibits a turns ratio of 8.5. An input voltage of 55 volts is converted to an output voltage of 0.8 volts. The passive *LC* elements, parasitic impedances, switches, and load behavior are identical for each branch. The performance is illustrated in Figure 6. The output voltage is stable around 0.8 volts with less than 3% ripple. Improved sinusoidal distortion and smaller current spikes are achieved as compared to a single branch high turns ratio converter. A 90% reduction in the magnitude of the current spikes is achieved by the distributed topology. Reductions in EMI levels are expected [5].

Assuming a 97% transformer efficiency, the maximum power efficiency of the distributed sinusoidal resonant converter is 89.8%, as compared to a 91.7% maximum power efficiency in a single branch sinusoidal resonant converter with the same step-down ratio. The distributed converter exhibits additional power losses due to the greater number of transformers and MOSFETs. The slightly reduced power efficiency can be compensated by the high step-down ratio conversion in DPA systems, leading to comparable or greater system power efficiency.

Due to the linear growth of the number of transformers and switches in the secondary stage, the area of the distributed sinusoidal resonant converter increases linearly with the number of branches. The growth in area is highly dependent on the type of transformer and switch. Due to the lower current flowing through each branch within the distributed resonant converter, switch with smaller size can be utilized. Smaller transformer can also be used due to the lower turns ratio. The area of each branch in the distributed sinusoidal resonant converter is therefore smaller than the single branch resonant converter. In one case study, the area increased by 84.1% in an eight branch distributed sinusoidal resonant converter as compared with a single branch sinusoidal resonant converter.

Note that the distributed converter topology is highly scalable. The number of branches is dependent on the circuit area, specific voltages, and performance requirements. This proposed distributed topology is particularly advantageous when high step-down ratio conversion is required, as in DPA systems. Due to the EMI mitigation characteristics [5], the distributed topology is highly applicable to noisy applications such as systems-in-package, IoT, and wireless devices.

V. Conclusions

A novel quasi-sinusoidal resonant converter operating at high frequencies for PoL DC-DC conversion is proposed. The converter exhibits a stable load voltage with less than 4% ripple and a fast transient response of less than 1 μs. A distributed topology for a sinusoidal resonant converter is introduced here, and exhibits a power efficiency of 89.8%. A reduction of nearly 90% in the magnitude of the current spikes is also achieved as compared to a single branch sinusoidal resonant converter with a similar step-down ratio. Due to the high step-down ratio and low EMI characteristics, the distributed topology is particularly effective in emerging applications such as systems-in-package and IoT devices.

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