Improved ZVS Criterion for Series Resonant Converters: A Simplified Approach

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ABSTRACT

The ultrafast switching capabilities and power density of MOSFET is greatly affected by the nonlinearity of the output capacitances. Conventionally, energy-based zero-voltage-switching (ZVS) criteria have been developed and applied to resonant converters with the aim to reduce switching losses. However, the nonlinear equations in the existing criteria bring about complexity and time consumption during calculations. To overcome the stated limitation, this paper theoretically analyzes a series resonant DC-DC converter (SRC) and develops a tailored simplified approach of calculating the time required to attain ZVS condition. The objective of the simplified approach is to reduce switching losses in the system for better efficiency. The analysis is verified by simulation based on the improved ZVS criterion.

Keywords: Series resonant converter, zero-voltage-switching, MOSFET nonlinear output capacitance.

I. INTRODUCTION

Zero-voltage-switching (ZVS) is a form of soft-switching technology whose target is to reduce or eliminate switching losses by using resonance technique of the inductor-capacitor tank to remove voltage in the power switch before turn-on [1]. This helps to increase switching frequency. In addition to limiting the circulating and the peak current, ZVS also helps in achieving a favourable trade-off between switching losses and conduction losses, thus leads to an enhanced overall performance of the resonant converter[2].

The energy-based criterion proposed in literature [3] takes into account the energy balance in the system to form a ZVS criterion. However, one of its major limitations is the method presented for computing the minimum time required to achieve ZVS condition for SRC is complex and time consuming. This is because the ZVS transition time equation is highly nonlinear.

The aim of this paper is to come up with a simplified approach for the highly nonlinear methodology in [3]. The proposed ZVS criteria approach offers minimized switching losses. This improves performance over a varied load range hence enhances reliability. Beginning with equivalent output capacitances [4], linear approximations are obtained. Due to this, despite the simulations results showing slight difference from the nonlinear comparison, the ZVS criterion is easily achieved.

In the subsequent sections, this paper delves into the theoretical simplification of the approach in [3] for the estimated minimum dead time for successful ZVS transition.

II. APPROXIMATION OF ZVS TRANSITION TIME FOR SRC

Fig.1 shows an equivalent circuit for full-bridge SRC during the switch dead time. According to literature, several methods have been proposed for replacing the nonlinear output capacitor, C_{oss}. One of such methods is the energy-equivalent capacitance $C_{eq,Q}$ and charge-equivalent capacitance $C_{eq,E}$ [4], shown in (1) and (2), respectively,

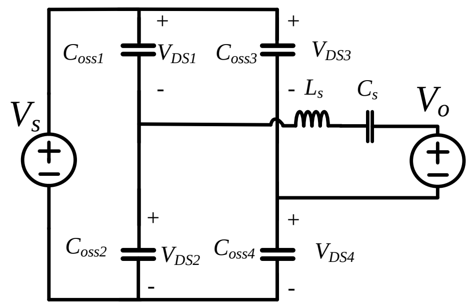

Fig. 1. Equivalent circuit for full-bridge series resonant converter during the switch dead time.

$$C_{eq,Q} = \frac{1}{V_s}\int_0^{Vs} C_{oss}(v_{DS})dv_{DS} \tag{1}$$

and

$$C_{eq,E} = \frac{2}{V_s^2}\int_0^{Vs} v_{DS}\, C_{oss}(v_{DS})dv_{DS} \tag{2}$$

those are calculated to give the same charge and energy as C_{oss} when the drain-to-source V_{DS} equals to the supply voltage V_S, respectively.

Given the nonlinear characteristics according to V_{DS} exhibited by the MOSFET's C_{oss}, the computations become tedious when the drain-to-source voltage across is changing, evident in (1). Therefore, a two-point approximation is be applied to offer linearized values. By use of Riemann summation method of left rule and right rule [5], estimations are obtained, and the average of their sum is estimated. The estimated stored charge $Q_{OSS,n}$ across C_{OSS} is shown in Table I and can be calculated as

$$Q_{oss,n} = \sum_{i=0}^{n} \Delta v_{DS} C_{OSS}(v_{DSi}) \tag{3}$$

where $a = 0$, $b = V_S$, $n = \text{intervals}$, and

$$\Delta v_{DS} = \frac{b-a}{n} \quad . \tag{4}$$

The interval used in this approximation is taken as 1 for simplicity of calculation and comparison. When the two estimated sums are obtained, they vary due to overestimation of the left rule and underestimation of the right rule. The sum of the two rules is averaged to achieve an approximate value of $Q_{OSS,n}$ which is found have lesser estimation error as compared to the separate rules.

The highly nonlinear equation approach proposed in [3] to calculate the minimum required time for ZVS to occur, t_{zvs}, is related to the resonant tank current i_r and the two output capacitances, C_{OSS1} and C_{OSS2}, on the same leg during the switch dead time. Due to these nonlinear capacitances, the bounded integral is complex. To simplify the equation, the equivalent charge capacitance in (1), is replaced with the voltage-dependent capacitance equation, and rearranging gives the estimated time for ZVS transition, $t_{zvs,est}$, as

TABLE I. Comparison of estimated values by Riemann Sum.

n=1	$Q_{oss,1}$ (nC)	Error (%)
Left Rule (LR)	75.105	5.78
Right Rule (RR)	68.031	4.18
Average of LR and RR	71.568	0.8
True Value	71	-

$$t_{zvs,est} = \frac{1}{i_r(t_1)}\left[C_{eq,Q1} + C_{eq,Q2}\right]V_S \qquad (5)$$

where $i_r(t_1)$ is the current at time t_1 during the switch dead time [3]. This simplified estimation of the time required to achieve ZVS condition is proportional to the equivalent capacitances as well as source voltage while inversely proportional to the resonant current.

III. SIMULATION VERIFICATION AND DISCUSSION

Simulation of a full-bridge resonant converter is conducted to verify this theoretical analysis. For comparison, similar to [3], Table II summarizes the simulation parameters. The values obtained for the estimated charge stored across the output capacitors using left rule, right rule and the average value of the sums are as predicted from the approximation. Compared to the exact value of 71 *nC* [3], the average of the sums portrays the least estimation error of 0.8 % when interval is taken as 1. The simplified approach in (5) estimates the $t_{zvs,est}$ to be 142 *ns* with the resonant current equal to 1 A [3] and both charge equivalent capacitances are calculated as 0.01775 *pF*. The estimated value has an error of 38 % as compared to the exact value of 230 *ns* [3]. Examining the exact equation in [3] and (5), the difference in the approximation error is mainly attributed to by the replacement of the upper and the lower nonlinear output capacitances on the same leg during switch dead time. Furthermore, considering binary classification, the estimated value and the exact value can be used to assess predictive performance of the simplified approach [6]. Taking t_{zvs} and $t_{zvs,est}$ as true positive (TP) and false positive (FP), respectively. The F1-score, a way to understand how well the proposed estimation approach is performing, for the two cases is calculated as

$$F1 - score = \frac{2TP}{2TP + FP + FN} \qquad (6)$$

and illustrated in Fig. 2. FN refers to a false negative case, but since there is no such case it equals to zero. As voltage goes to V_S, the predictive performance has constant difference due to calculated error as shown in table III.

IV. CONCLUSION

In this article, a simplified approach to improved ZVS criterion for series resonant converters is proposed. An analysis of ZVS energy-based criterion for SRC is conducted having considered the energy balance in the converter circuit. To eliminate the complex and time-consuming assessment of equations containing nonlinear output capacitances, linear equivalent capacitances in addition Riemann summation methods of left rule and right rule are utilized. Therefore, the minimum switch dead time for ZVS transition calculation approach is simplified. The simplified approach is applicable by extension to other modulation strategies proposed in literature, and thus will be our subsequent topic of research.

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TABLE II. Simulation parameters.

Parameter	Symbol	Value	Unit
Input voltage	V_S	400	V
Output voltage	V_O	400	V
Resonant tank capacitor	C_r	4.5	*nF*
Resonant tank inductor	L_r	600	*μH*
Switching frequency	f_S	100	*kHz*
Intervals	n	1	-
Lower bound	*a*	0	V
Upper bound	*b*	400	V

TABLE III. Comparison of time for ZVS transition

Exact t_{zvs} (*ns*) [3]	Simulation $t_{zvs,est}$ (*ns*)	Error (%)
230	142	38 %

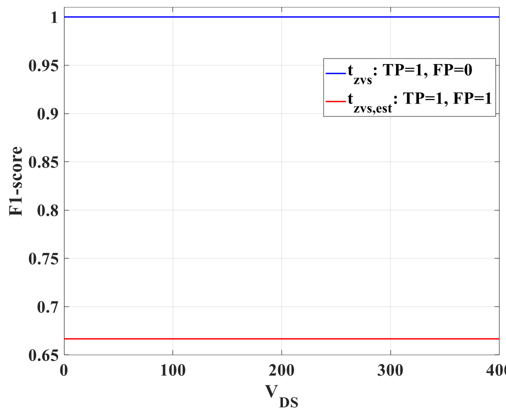

Fig. 2. F1-score for the exact and estimated cases.

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