Design Guidelines on the Effect of Resonant Transitions of Forward Converter on Efficiency with Active Clamp

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Abstract-Design guidelines are proposed on how to achieve efficiency benefit from the active clamp technique used in single-ended forward converters. The presented guidelines are analyzed and tested based on the effect of resonant transitions on efficiency from three design parameters of magnetizing current, delay time, and LC resonant frequencies.

I. INTRODUCTION

This paper is motivated to develop design guidelines how to achieve efficiency benefit from the active clamp technique used in single-ended forward converters (ACFC) from its reduced voltage or zero voltage switching. The attractions of such technique are multi-fold to reduce power losses especially switching power losses, mainly including zero or close to zero voltage (i.e., valley voltage as called) switching, ZVS or VVS, that can be achieved and naturally reduces the switching losses. Also, primary leakage inductance energy is recycled / regenerated to make further energy savings. There are numerous publications dedicated to the topic, for example [1-10], to improve the efficiency by properly selecting the transformer magnetizing current and the delay time [3-6], while the required LC resonances are usually not addressed enough. This may lead to un-proper designed LC resonances and compromise efficiency benefit which would be otherwise possible with better results. In the publications, while it is commonly agreed that efficiency improvement can be achieved by ZVS or VVS from reducing switching losses, it is yet in common to know if total efficiency can be improved. The argument as well as its supported test evidence states that excessive magnetizing current and delay time leading to ZVS may increase conduction losses to such an extent that total efficiency actually becomes lower. Although various methods have been proposed to reduce the required magnetizing current to achieving ZVS such as adding extra primary or secondary serial inductance [8] and using MagAmp [7], a total efficiency benefit achievable from various applications are not clearly agreed.

This paper, based on the re-examination of existing methods, intends to develop design guidelines based on the effect of resonant transitions to maximize total efficiency benefit from the active clamp technique. Basic design guidelines are proposed, focusing on how the ZVS/VVS can be achieved, when, and at what conditions, the ZVS/VVS can provide efficiency benefit. Among them, the paper considers two design rules that should be checked at first hand.

The first design rule is to check energy balance, i.e., how much net energy-saving can be obtained from the ZVS/VVS. This should be addressed as a first check while usually set as default and not clearly indicated in the past. A designer is not able to stay on design track to make efficiency improvement unless knowing what the best efficiency target they could aim at. Then it comes to the next step to check how much energy would be wasted as the increase of conduction losses due to ZVS or VVS succeeding conditions. The paper shows by summarizing that the efficiency benefit achievable from an ACFC with four factors (a) operation voltage; (b) operation switching frequency; (c) switch characteristics; and (d) design parameters including magnetizing current $I_m$, delay time $t_{DEL}$ and two LC resonances, $\omega_R$ and $\omega_{CL}$.

The second design rule is to check if the resonant timing is set up properly with the three parameters involved in the resonant transitions. The three parameters should be adjusted and tuned up together with the first three factors in order to achieve efficiency benefit from an ACFC. Also, the work of this paper shows that properly designed VVS, instead of pursuing true ZVS, is in general a criterion to follow in order to maximize total efficiency. Among three parameters involved in the ACFC transitions, LC resonances setup for an ACFC should be emphasized equally important to the other two parameters, magnetizing current and delay time, which seems not addressed as much as it should be in the published materials.

This paper is organized as follows. First, it reviews how energy can be saved, and efficiency can be improved, from the reduction of switching losses using the active clamp with typical MOSFETs operation. Then, it re-examines the active clamp technique used in single-ended forward converter to improve efficiency by reviewing existing design methods. Following that, the paper presents the developed design guidelines to maximize total efficiency by properly setting up the magnetizing current, the delay time and the LC resonances. After that, presented are efficiency test results and comparison based on two examples, one from an off-line application, and the other from a telecom application, to show effectiveness of the developed guidelines.
II. REVIEW OF ENERGY-SAVINGS FROM ACTIVE CLAMP WITH MOSFETS OPERATION

The active clamp technique used in single ended forward converters improves efficiency in several ways including:

- Energy stored in primary leakage inductance is regenerated; the energy stored in the transformer primary winding leakage inductance is first dumped to the primary main switch \( C_{DS} \) and clamp capacitor \( C_L \) when the primary main switch is turned off. Then the energy stored in the capacitance can be regenerated fully or partially back to the source with proper design. This part of energy will then be saved from the active clamp technique.

- Energy stored in primary main switch capacitance \( C_{DS} \) is regenerated by ZVS or VVS on; noticed that capacitance \( C_{DS} \) represents equivalent capacitance, usually including the switch \( C_{DS} \), the transformer winding, the secondary side referred back to the primary, and all other stray capacitance. The energy stored in these areas can be re-generated to the source by active clamp technique. But to achieve such regeneration, it will require a proper design and will be discussed later.

- V-I cross conduction power losses minimized from ZVS or VVS.

Among them, the very critical aspect is its reduced voltage switching or zero voltage switching [1-10]. The reduced voltage VVS or ZVS helps reduce energy losses. Then it helps improving the efficiency.

Active clamp technique uses LC resonance to realize the VVS or ZVS. It is well known that an LC resonance in its essence is caused by the energy flowing between the magnetic field and the electric field. In circuit theory, an inductance \( L \) is used to represent the magnetic field and a capacitance is used to represent the electric field. As such, to achieve VVS or ZVS, a proper arrangement of energy flowing becomes a key design point in active clamp technique.

The energy stored in the electric field as in a capacitor is expressed as,

\[ E_C = \frac{1}{2} \times C_{DS} \times V_{DS}^2 \] (1)

its switching power then expressed as,

\[ P_{C,sw} = \frac{1}{2} \times C_{DS} \times V_{DS}^2 \times f_{sw} \] (2)

In the above, noticed that MOSFET \( C_{DS} \) is varying with its voltage \( V_{DS} \). Knowing this is helpful to understand resonant transition behavior. Fig. 1 illustrates one example of \( C_{DS} \) variation with respect to \( V_{DS} \). Fig. 2 demonstrates associated energy change in \( C_{DS} \).

As can be seen, the switching power from a capacitor is proportional to its voltage squared. When \( C_{DS} \) stored energy dissipated through the MOSFET channel on resistance each switching cycle, the energy will become power losses. The higher the \( V_{DS} \) of MOSFET at turning on, the higher the switching losses.

To be able to make ZVS or VVS, the energy stored in the electric field has to be diverted out before starting each switching cycle. This requires the magnetic field has enough energy capability to flow out the electric energy to the magnetic. In other words from a circuit point of view, the transformer magnetizing current has to be high enough. If magnetizing current high enough, the energy stored in the capacitance is then able to flow out of \( C_{DS} \) to make \( V_{DS} \) lower or zero. Hence, a high magnetizing current becomes a condition to achieve reduced voltage at switch turning on. But this is only one side of the design consideration to make energy savings. On the other side, a high magnetizing current will cause higher core losses and higher ohmic losses. Hence, efficiency improvement is dependent on the net energy difference after balancing the savings and additional losses.

Fig. 3 presents a visual example to show how much efficiency drop with respect to different voltages at MOSFET turning on. Efficiency results were obtained from a 300W converter at 20% load level. For simplified comparison, Fig. 3 only considers the difference of energy stored in \( C_{DS} \) with respect to its \( V_{DS} \). Fig. 3 demonstrates that potential efficiency improvement is obtained from different voltage differences. For example almost a two percent efficiency improvement obtained when \( V_{DS} \) changed from 350V to 150V. While only 0.12% from 50V to zero volts. This example gives us a hint when and where a design can be benefit more from an ACFC.

This example, on the other hand, also indicates maximum achievable efficiency benefit from active clamp technique should be observed and cannot be exceeded. Knowing this is critical for a designer, since it then does not make sense to pursue further efficiency improvement after the efficiency reaches certain value. In general, ZVS may not provide further efficiency improvement and may adversely affect efficiency result if further increasing the magnetizing current makes conduction losses increase faster than savings from switching losses reduction such that total efficiency after the energy balance is actually reduced. The switching loss from a MOSFET turning-on is proportional to its capacitance, its voltage squared at turning-on, and its switching frequency. In high voltage applications such as off-line applications, efficiency improvement can be more easily achieved. While in the low voltage applications such as telecom with 48V input voltages, efficiency improvement may not be achieved with currently used switching frequency in the range of a few hundred kilo hertz.

In this example, the energy savings from transformer leakage inductance energy recycle and V-I cross conduction power loss reduction are not considered, but they are ready to be added to the balance sheet to estimate net energy differences. In the next section, we are going to discuss how to make the energy balance to achieve ZVS or VVS.

III. RE-EXAMING ACTIVE CLAMP IN SINGLE-ENDED FORWARD CONVERTERS
Working principles of the active clamp in a forward converter can be easily found in numerous published materials since it was first proposed [10]. This paper intends to emphasize three key parameters for the design purpose to take advantage of its resonant transitions on the potential efficiency benefit, namely the magnetizing current, the delay time and the LC resonances. The first two have been emphasized in various publications. The third one seems has been taken for granted while it should be properly determined for a design as an important factor to achieve better efficiency. For convenience, a high side active clamp forward converter is used in this paper as shown in Fig. 4. The developed design guidelines are applicable to a low side active clamp forward converter.

Fundamentally, the active clamp technique relies on the LC resonances to divert the energy from the electric field to the magnetic field in order to reduce the capacitor’s charged energy then reduce its associated voltage when Q1 is turned on. As shown in Fig. 4, energy diversion from C to L requires adequate time. Extra energy may be needed if some energy flows outside instead of between L and C during the diversion time, for example considering the energy requirement effect reflected from the secondary side circuit.

LC resonances should be properly determined to provide adequate delay and current flowing direction during the transition in association with the switching frequency. As shown below, proper setup of LC resonances can help to achieve VVS or ZVS.

The requirement of longer delay time, resulted from improper design of LC resonances, may help the energy diversion as discussed in published materials to get the voltage closer to zero value. While a delay time may adversely affect the efficiency. During the time interval, secondary side synchronous rectifier may not obtain enough driving which resulting in more power losses. More losses may also come from the free wheeling loop change by adding in transformer secondary winding thus more dc losses yield.

Proper LC resonances setup can help to reduce un-necessary long time delay (a) to allow the magnetizing current reversing its direction before turning off Q2 and (b) to allow quicker divert the energy from C to L. A proper setup may be arranged from a higher resonance frequency to help the magnetizing current able to reverse direction before turning off the clamping MOSFET Q2 as shown in Fig.4.

Typically two LC resonances need to be determined. Both occur with magnetizing inductance \( L_M \). The first resonance, \( \omega_R \), is between \( L_M \) and the equivalent \( C_{DS} \) (ignoring leakage inductance as shown in Fig.5):

\[
\omega_R = \frac{1}{\sqrt{L_M \times C_{DS}}} \tag{3}
\]

The Q1 \( V_{DS} \) is experiencing this resonance during t1 to t3 and t6 to t8. For resonance \( \omega_R \), its design value is in contradictory for Q1 on and off. For Q1 on, a higher \( \omega_R \) is in favor since this can help quicker energy diversion with less delay time for VVS/ZVS turning on purpose. While for Q1 off, a lower \( \omega_R \), achieved from a higher \( C_{DS} \), may behave better to allow more time for Q1 channel turning off then reducing/eliminating V-I cross area. In reality, however, resonant frequency, \( \omega_R \), may be designed with only one value. Compromise on both needs may have to be made on the efficiency benefit and components’ stress concerns.

The resonance \( \omega_R \) is determined by \( L_M \) and equivalent \( C_{DS} \). Its value may have limited flexibility to select. To compensate the limitation of \( \omega_R \), active clamp control needs to have a delay time to achieve a reduced \( V_{DS} \). As said, a long delay time compromises total efficiency. It also reduces applicable duty cycle range. In such a situation, lower switching frequency may help a design if such an option is feasible. To make these trade-offs, trial-and-error method is usually good and effective.

The second LC resonance is formed by \( L_M \) and the equivalent clamp capacitor \( C_{Cl} \) if ignoring \( C_{DS} \):

\[
\omega_{Cl} = \frac{1}{\sqrt{L_M \times C_{Cl}}} \tag{4}
\]

As shown in Fig. 6, when Q1 turns off, its \( V_{DS} \) is experiencing resonance, \( \omega_{Cl} \), from t3 to t6. On the energy diversion to achieve the target of ZVS/VVS, reversing the magnetizing current direction and maximizing its value before t6 are desirable. In this time interval, the magnetizing current can be expressed in an approximation of co-sinusoidal function:

\[
i_{M}(t) = I_M \cos(\omega_{Cl}(t-t_i)) \tag{5}
\]

As noticed in Fig. 6, the associated voltage \( V_{DS} \) change is shifted to a center around \( V_{IN} \). For ZVS/VVS design consideration, it is desirable that \( i_M(t) \) at \( t = t_6 \) reaches its negative maximum value as much as possible to maximize its energy diversion capability for time interval t6 to t8. This would require,

\[
\cos(\omega_{Cl}(t_6-t_i)) = -1 \tag{6}
\]

resulting in

\[
\omega_{Cl}(t_6-t_i) = \pi \tag{7}
\]

Since the time from t3 to t6 is approximately equal to Q1 off time minus one delay time \( t_{DEL} \). Equ. (7) can then be approximated as

\[
\omega_{Cl} \times (t_{OFF} - t_{DEL}) = \pi \tag{8}
\]

Equ. (8) demonstrates an important design guideline to help achieving ZVS/VVS. To achieve this, it needs to make resonance frequency \( \omega_{Cl} \) properly designed. In reality, \( t_{OFF} \) is varying with respect to both line and load regulation during operation, while only one resonant value can be designed. To maximize efficiency benefit achievable range with determined parameters such as switching frequency and magnetizing inductance, trade-offs have to be made with \( C_{Cl} \) value and its voltage stress. From this perspective viewpoint, the right-hand side of Equ. (8) may be altered to a value less than \( \pi \).

From t6 to t8, the magnetizing current can be approximated in a similar equation as shown

\[
i_{M}(t) = i_{M1}(t_6) \cos(\omega_R(t-t_6)) \tag{9}
\]
To force $V_{DS}$ approaching to zero, a corresponding design guideline is then obtained based on Equ. (9)

$$\cos(\omega R(t - t_b)) = 0$$

which results in

$$\omega R(t - t_b) = \frac{\pi}{2}$$

(10)

From t6 to t8, the time interval is actually the programmed delay time. Then the guideline becomes

$$\omega R \times t_{DEL} = \frac{\pi}{2}$$

(12)

Again, the design emphasis should be made to achieve reversed direction of the magnetizing current before turning off Q2 at t6. If the direction is reversed after t6, the energy diversion from the electric field C to the magnetic field L may require a longer delay time resulting in less efficiency from more conduction losses. The current with its direction reversed before Q2 turns off is important to help achieving a reduced voltage when Q1 turns on, which helps to reduce the required delay time. Usually a smaller delay time can help to get a better efficiency from this paper’s work as well as from the published work such as [4].

IV. PROPOSED DESIGN GUIDELINES

Typical design procedures for an active clamp forward converter are very well documented and can be referenced from many publications, for example in reference [9]. While on the efficiency further improvement from the effect of resonant transitions, this paper considers the followings that should be noted and checked.

- Based on MOSFET parameters, switching frequency, and input voltage, estimate how much gross energy can be saved based on estimation of switching power losses can be resulted.

- Estimate the increased conduction losses due to the ZVS/VVS succeeding requirement. Note that VVS is in general a better criterion to achieve better efficiency.

The optimal point can then be found as an efficiency target for the design based on the above two estimations.

- Estimate the required magnetizing current using energy balance relationship developed [2-3, 7-9]:

$$\frac{L_M}{C_{DS}} \left( N \times \frac{2}{2 - \frac{1}{2}} \times \frac{\cos(\omega R \times t_{OFF} - t_{DEL})}{2}] \times [1 - V_m] > V_m$$

(13)

where N – transformer turns ratio; $V_{O,misc}$ – secondary total voltage drop from the transformer winding to output terminals; $L_{eq}$ – equivalent current flowing out of $L_M$ and $C_{DS}$ resonant loop, its associated energy may include secondary diode reverse recovery energy and secondary MOSFET total gate charge. A lower magnetizing inductance may include secondary diode reverse recovery energy and secondary MOSFET total gate charge. A lower magnetizing inductance plays an important role. Its resulted higher magnetizing current can provide an adequate energy to make energy diversion. A lower $L_M$ can make higher $\omega R$ easier then resulting in smaller $t_{DEL}$.

- Estimate the required two LC resonant frequencies, the clamp capacitor’s maximum voltage and the delay time needed.

- Estimate the overall efficiency with ZVS and different VVS at light load (say 20% load), medium load (say 50% load) and full load to get improved total efficiency across the load range.

V. DESIGN EXAMPLES, TEST RESULTS, AND COMMENTS

Example 1 - off-line application example

Input voltage = 390 V
Output voltage = 12 V
Output power = 300 W,
Switching frequency = 150 kHz (after adjustment with $\omega R \times \omega CL$, $t_{DEL}$ and $L_M$).

Design parameters for ZVS/VVS, $L_M = 0.65$ mH, $C_{CL} = 4.7$ nF, $C_{DS} = 500$ pF at $V_{DS} = 25V$, $t_{DEL} = 280$ ns. The resulted $\omega R$ and $\omega CL$ are 1,754 x 10³ rad/s and 572 x 10³ rad/s, respectively. Both resonance frequencies were obtained with trade-offs among MOSFET voltage stress and proposed design guidelines. The test board is shown in Fig.10. Primary main MOSFET turning on with ZVS was achieved when the load current less than 2 A as shown in Fig.7. When load current became higher, the ZVS became VVS and at full load (25 A), the MOSFET turning on voltage $V_{DS}$ was measured as 184V as shown in Fig. 8. Significant efficiency improvement was observed based on the design guidelines presented in this paper. The efficiency test results are shown in Fig. 9. In this figure, although marked is only the magnetizing inductance difference, the efficiency difference from the two magnetizing inductance indicators is yet based on the fine-tuning of the delay time $t_{DEL}$, and the adjustment between $\omega CL$ and the switching frequency to follow design guidelines described by Equ. (8 ) and Equ.(12). The figures illustrate the achieved efficiency with respect to the different magnetizing inductance, the delay time and the LC resonances across the load range.

Example 2 - telecom application example

Input voltage = 42 V
Output voltage = 3.3 V,
Switching frequency = 300 kHz.

The test was made based on a board designed for telecom application as shown in Fig. 11. When $L_M$ changed from 95uH to 25uH, it was observed that primary main MOSFET $V_{DS}$ at tuning-on was less than 3V as shown in Fig. 12. But the resulted efficiency was reduced significantly. This shows that pursuing ZVS without considering additional losses may not improve efficiency.

Efficiency comparison

$\textbf{L}_M = 95$ $\mu$H
Output Load = 1 A 5 A 10 A
Efficiency = 68% 86% 90%

$\textbf{L}_M = 25$ $\mu$H
Output Load = 1 A 5 A 10 A
Efficiency = 54% 80% 88%
VI. CONCLUSIONS

This paper has reviewed existing analysis and design methods for active clamp forward converter. Design guidelines are developed and proposed to maximize total efficiency based on the effect of the resonant transitions of forward converter with active clamp. The developed guidelines emphasize three design parameters (a) magnetizing current; (b) delay time; and (c) LC resonances. One example is provided from off-line applications to show effectiveness of the proposed design guidelines. The other example is presented from telecom applications to show ZVS may not provide efficiency benefit in the low voltage applications.

ACKNOWLEDGMENT

The author wishes to thank his colleagues, Richard Garvey and John Bottrill, for their valuable discussions during this work.

REFERENCES

Figure 4 Typical single-ended forward converter with high side active clamp.

Figure 5 Transformer model without considering ohmic and core losses.

Figure 6 Typical switching waveforms in an active clamp forward converter.

Figure 7 ZVS observation from an off-line application design with active clamp forward converter following proposed design guidelines.

Figure 8 VVS observation from an off-line application design with active clamp forward converter following proposed design guidelines.

Figure 9 Comparison of efficiency using proposed design guidelines.
Figure 10 Test board layout of an off-line application design.

Figure 11 Test board layout of a telecom application design.

Figure 12 ZVS observation from a telecom application design with active clamp forward converter.