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A Novel Regenerative Snubber Circuit for Flyback Topology Converters

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Abstract

Switch mode power suppliers based on isolated flyback topology have voltage stresses on semiconductor switches caused by transformer leakage inductance. Those voltage stresses have to be mitigated by implementing active or passive clamp preferably with partial leakage energy recovery. In this paper a new integrated semi-active regenerative (lossless) snubber is proposed. The proposed snubber topology is featured by the snubber inductor integrated into main transformers thus decreasing component count and saving the PCB space. Partial coupling of snubber inductor with a secondary side makes it possible to recover part of the transformer leakage energy directly to the secondary side with potential to increase snubber efficiency. The operation of the proposed snubber is analyzed and simulation results are presented. Interesting is that with the proposed snubber, along with achieved voltage stress limitation and transformer leakage energy recovery, various side effects can be reached like reduction of RMS current in secondary side, ZCS and ZVS modes for secondary side rectifier and primary main switch.

Keywords: regenerative snubber, flyback, converters.

1. Introduction

The improvements in power semiconductors and magnetic components make converters based on flyback topology more efficient and hence makes it more attractive to implement flyback topology into practical applications. Flyback topology finds broadening usage due to its low component count, simple schematics, robustness and possibility to provide galvanic isolation. One of the major challenges encountered here by flyback designers is the mitigation voltage stresses of semiconductor switches caused by flyback transformer leakage inductance. There are several solution proposed to limit voltage spikes on a main switch but the most desirable of them are non-dissipative and regenerative snubber circuits to improve efficiency.

In a scientific literature there are well known active clamp snubbers with regenerative capabilities [1]-[3]. Active clamp can help effectively recover the transformer leakage energy clamped in snubber capacitor; it can also help to provide zero voltage switching mode for the main power switch. But all of these benefits come with the complexity of an active clamp. Other feature of an active clamp in flyback topology, that it increases current RMS value for a secondary circuit and high current peak for secondary rectifier diode before switch off. Also active clamp reduces the robustness of a flyback, because the auxiliary clamp switch commutates snubber capacitor to output capacitor through transformer leakage inductance.

There are also number of passive non-dissipative snubber circuits for flyback converter [4]-[11]. These passive snubbers significantly and cost effectively reduce turn off switching losses and regenerate leakage energy from snubber capacitor. They recover energy back to power supply DC bus or store in the magnetizing inductor of a flyback transformer. There are some integrated regenerative circuits [8]-[11], that offer advantage of reducing component count and circuit simplification. Other advantage of these passive integrated regenerative snubbers is that they can partially recover transformer leakage energy forward to the secondary output, thus can potentially demonstrate higher efficiency. The considered regenerative snubbers work in discontinues conduction mode or resonant mode thus with increased RMS in snubber circuits.

There are also some snubber solution [12], [13] that is worth to mention in this article. Their idea is quiet straight forward and involves commutation of clamp capacitor to the input for stored transformer leakage energy recovery. Snubber [13] is a passive one and embodies additional auxiliary switch that synchronously with the flyback main switch commutates clamp capacitor to an input through the auxiliary inductor. These two mentioned snubbers are featured with the complex structure but do not compromise the robustness of the flyback topology.

In this paper a novel regenerative passive snubber circuit integrated with the flyback transformer is considered. The proposed snubber [14] have potential to recover most of the energy to the secondary output. The behavior of the proposed solution is dependent on particular realization, multiple parameters. One of the promising recover strategies

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have been analyzed. The simulations have been provided to reveal the advantages of the proposed solution. Stage-by-stage consideration has been given, and equivalent schematics have been provided for stages where it is needed.

2. The proposed regenerative snubber circuit for flyback topology

The advantage of the proposed snubber have been achieved by integration of auxiliary inductance with the main transformer, thus the transformer have the third auxiliary winding now. The advantage with this is that the energy can be recovered directly to the secondary output with potential to increase efficiency. The principal schematic of the proposed recovering solution is presented in Fig.1.

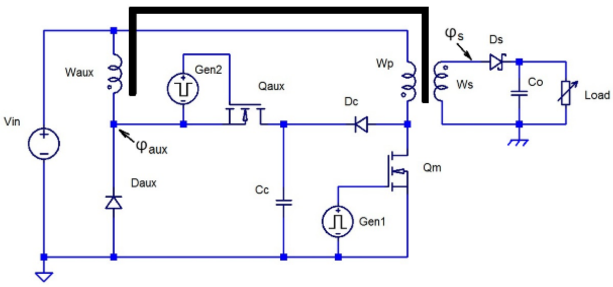

Fig 1. The proposed regenerative integrated snubber circuit and flyback converter

On Fig.1 one can see a flyback topology converter with a clamp voltage limiter consisting of clamp capacitor Cc and clamp diode Dc, and to drain clamp energy here is the circuit formed by auxiliary transistor Q_{aux}, auxiliary diode D_{aux} and auxiliary transformer winding W_{aux}. The auxiliary switch Q_{aux} is synchronized with the main switch and can be driven passively or actively. The synchronization and driving of Q_{aux} with the main switch can be accomplished by tapping from Waux winding or by means of additional 4th winding. It is clearly seen that the behavior of the circuit is highly dependent on parameters like leakage inductance between transformer windings and auxiliary winding, turns ration W_{aux}/W_p. We propose to start studying of the schematic on Fig. 1 with some clear assumptions: the auxiliary winding turns are equal to the primary winding turns, $W_{aux}=W_p$; coupling between W_{aux} and other transformer windings are weaker than coupling between primary W_p and secondary Ws windings. For analytical proposes we consider that all semiconductor switches are ideal. We consider the case when auxiliary transistor Q_{aux} switches in an antiphase to the main transistor Q_m, and here is a delay after Q_{aux} switch off and Q_m turn on. With these assumptions let's consider six operating stages in a steady state condition for the circuit on the Fig.1, and they are all presented in a Table 1.

Table 1. Switches operation scheduler.

Stage	1	2	3	4	5	6
Qm	ON	off	off	off	off	off
Qaux	off	off	off	ON	off	off
Ds	mostly off	ON	ON	ON	ON	ON
Dc	off	ON	off	off	off	off
Daux	off	off	off	off	ON	off

The equivalent circuit diagrams are given in Fig.2.1-2.6 for each of six stages, where Vaux - auxiliary winding voltage during non-conducting condition, Vp- primary winding voltage during non-conducting condition, Vo - output voltage, Vc - clamp capacitor voltage.

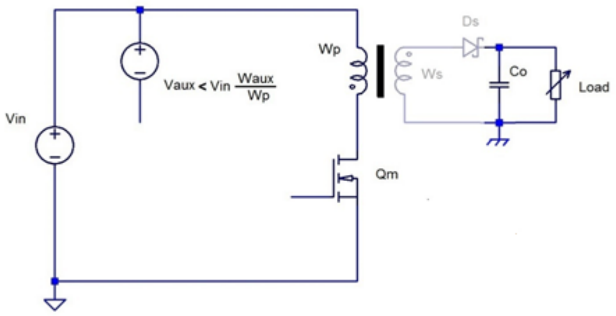

Fig 2.1. The first stage of the equivalent circuit diagrams

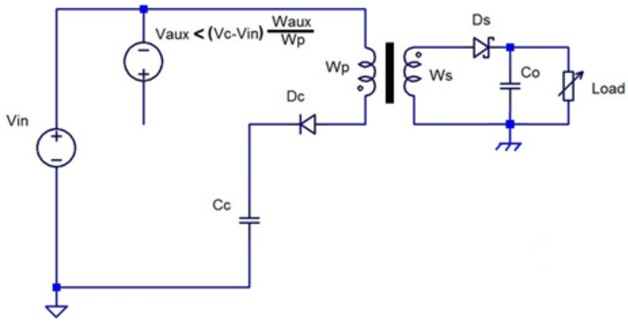

Fig 2.2. The second stage of the equivalent circuit diagrams

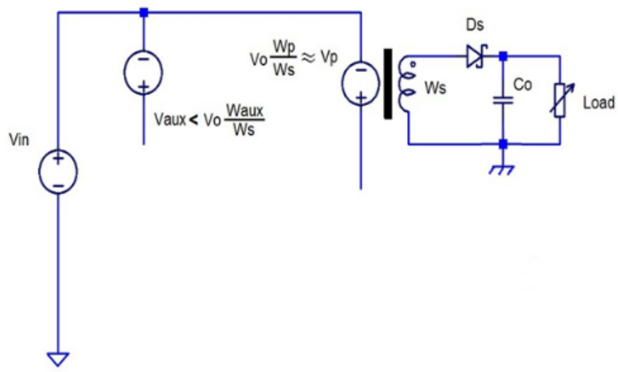

Fig 2.3.The third stage of the equivalent circuit diagrams

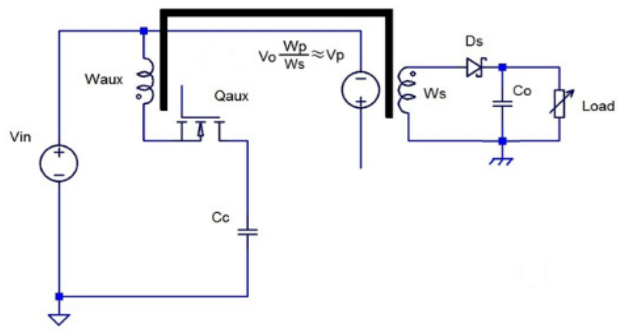

Fig 2.4. The fourth stage of the equivalent circuit diagrams

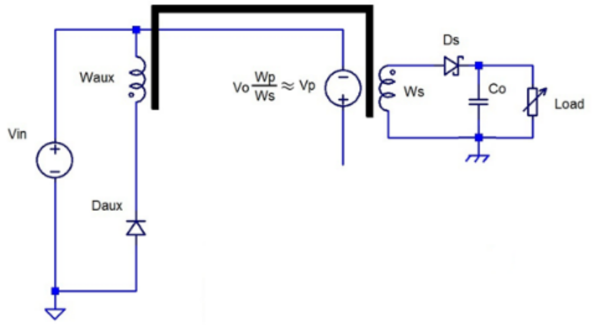

Fig 2.5. The fifth stage of the equivalent circuit diagrams

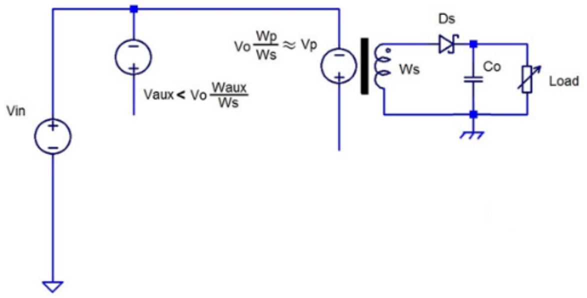

Fig 2.6. The sixth stage of the equivalent circuit diagrams

The waveforms have been generated in SPICE simulation software LTspice for the particular circuit parameters: transformer magnetizing inductance L_m=6400uH, coupling coefficient between primary and secondary windings 0.98, coupling coefficients between auxiliary to primary winding and between auxiliary to secondary windings are both 0.8; switching frequency about 67kHz; input voltage V_{in}=400V, output voltage 14 V and output power 145 W. The duration of the stages and simulated operation waveforms are presented in Fig. 3.

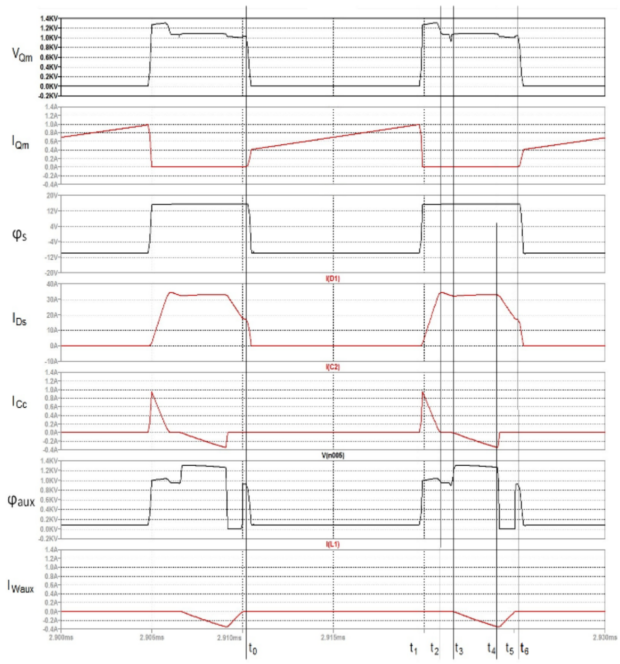

Fig 3. Simulation waveforms of the flyback converter circuit with the proposed regenerative snubber. V_{Qm} - drain to source voltage on the Q_m switch, I_{Qm} - current of the Q_m switch, φS and φ_{AUX} are the potentials of the corresponding nodes on secondary and primary sides (see Fig.1), I_{Ds} - current of the secondary side diode, I_{Cc} - current of the clamp capacitor C_c.

From Fig. 3 one can see that in our particular study case the auxiliary winding current flows in discontinues conduction manner. We will consider the case in which the main switch Q_m turns on at the time moment t0 after the current in auxiliary winding W_{aux} calms down to zero. By the moment t0 all primary side semiconductor switches are non-conducting only secondary diode Ds is conducting current to the output helping the flyback transformer to discharge it's remaining power through secondary winding W_s.

Stage 1 (t0-t1)

In this stage, see Fig. 2.1 main switch Qm is turned on, the transformer primary side Wp is connected to the input mains V_{in}, the secondary current rapidly goes down. After the output rectifier D_s gets reversed biased the transformer starts to gain power. On Fig. 2.1 the secondary winding Ws and rectifier diode D_c are partially shadowed, because most of the stage time they do not provide any current. At the same time the auxiliary diodes D_c and D_{aux} remain non-conducting. Clamp diode D_c is under reversed voltage of the clamp capacitor C_c. On the auxiliary winding W_{aux} here is a reflected voltage from the primary winding W_p, and because in this specific example it happened that W_p=W_{aux} thus the voltage applied to the auxiliary diode Daux is near zero. Actually diode D_{aux} under slight stress of reversed voltage because reflected voltage on W_{aux} is less than input voltage by voltage drop on equivalent primary side leakage inductance. The auxiliary winding is non-conducting, and the auxiliary switch Q_{aux} is under stress of clamp capacitor voltage.

Stage 2 (t1-t2)

At the moment t2 the main switch turns off, see Fig. 2.2 and the transformer primary current starts charging clamp capacitor C_c through the diode D_c until transformer leakage energy is depleted, that happens by the time moment t2. During this stage secondary diode current rises from zero. The reflected voltage on the auxiliary winding W_{aux} equals to the clamp voltage minus voltage drop on a leakage inductance of the transformer, thus it is the good moment for switch Q_{aux} to turn on. But we will make some longer delay before Q_{aux} turns on. The delay duration is optional, and may not last for two stages as we made. As the potential of Q_{aux} source terminal φ_{AUX} is lower than the clamp voltage, therefore internal diode of Q_{aux} as well as diode D_{aux} are remain non conducting.

Stage 3 (t2-t3)

Equivalent schematic of this stage is on Fig. 2.3. By the moment t2 the transformer leakage energy is depleted and diode D_c is closed. Here is still some time after the main switch Q_m turned off and before the auxiliary switch Q_{aux} turns on. During this time interval transformer primary and auxiliary windings are non-conducting, all semiconductors on the primary side are non-conducting. Only transformer secondary side discharges energy gained at stage 1 into output through the diode D_s. In this short stage current of the secondary side decreases.

Stage 4 (t3-t4)

At the moment t3 the auxiliary switch Q_{aux} turns on in order to discharge the clamp capacitor C_c, Fig. 2.4. Thus the capacitor C_c discharges directly into secondary side through the coupled windings W_{aux} and W_s, also onto the transformer leakage and transformer magnetizing inductance. The linear current rise on W_{aux} is determined by the leakage inductance:

$$\left(Vo \times \frac{Waux}{Ws} - Vc\right)/L_{aux\text{-}s} \quad (1)$$

where $L_{aux\text{-}s}$ is the equivalent leakage inductance between auxiliary and secondary sides. Because of the leakage between W_{aux} and primary W_p the reflected voltage on W_p is not big enough to open clamp diode D_c and hence primary winding remain non-conducting. From moment t3 secondary current slows down it's decrement and in our particular case we can observe some increasing due to energy supply from clamp C_c through auxiliary switch Q_{aux}. It is possible to select the value of leakage inductance and duration of stage 3 to make secondary current flat during conduction of the secondary rectifier D_s, from time t3 to t4, thus RMS current could be reduced. Simulation shows that if we made more time for Q_{aux} to be open, for example at the expense of time delay between Q_m turn off and Q_{aux} turn on (stages 2,3), then the clamp voltage would be lower due to increased discharge time and secondary current slope would be declining. Also simulation shows that decreasing the leakage between auxiliary winding and other transformer windings will reduce the clamp voltage as the discharge rate will be faster, will increase peak current for Q_{aux} and increase upward slope of the secondary current.

Stage 5 (t4-t5)
During this time period, see Fig. 2.5, the auxiliary switch turns off but here is some delay up to the time moment t5 then the main switch turns on. At the time t4 when Q_{aux} switches off auxiliary winding current starts to flow through auxiliary diode D_{aux} until it diminishes to zero. Thus the leakage energy associated with W_{aux} fully discharges back to the input. As a result the clamp energy fully recovered mostly forward to the secondary output, partly back to the input and partly in the form of transformer magnetizing energy gained at stage 5 from clamp C_c through winding W_{aux}. While W_{aux} current depletes at the same time secondary diode Ds current goes down as current from clamp capacitor no longer feeds secondary output and leakage associated with Waux exhausts. Magnetizing current gained at stage 5 also starts to flow in secondary side reducing diode D_c current in forward direction! It is potentially possible to make soft turn-off of the diode D_c and soft turn on of Q_m by turning parameters of a transformer, for example it could happen if the flyback topology was closer to the discontinues conduction mode. Delay duration between Q_{aux} turn-off and Q_m turn-on should be taken as long just to decrease secondary current as much as possible before the main switch turns on. But in our particular case for the research purposes again we made this delay to last for one more additional stage.

Stage 6 (t5-t6)
Equivalent schematic of this circuit is on Fig.2.6. From the time moment t5 up to the moment t6 both auxiliary Waux and primary Wp windings are non-conducting. All semiconductors on the primary side are switched off. The flyback transformer continues to provide remaining energy to the output secondary side through the diode Dc with descending secondary current.

4. Conclusions

The proposed novel regenerative passive snubber circuit integrated with the flyback transformer have less magnetic component count, thus compact and saves PCB space. The snubber recovers leakage energy to the secondary side output and back to input on primary side. The better the coupling coefficient between auxiliary and secondary transformer windings the more portion of the transformer leakage energy is recovered directly to the secondary output. This is a promising feature to increase the snubber efficiency. The value of a magnetic leakage between auxiliary and main transformer windings influences the RMS currents of the secondary side. The simulation shows that the leakage parameter could be adjusted to reduce secondary side RMS.

The synchronization and driving of an auxiliary switch of the proposed snubber could be done with tapping from the auxiliary transformer winding or with help of an additional forth transformer winding. This driving solution could help keep snubber implementation cost-effective. Slight delay between main switch turn-off and auxiliary switch turn-on facilitates ZVS for auxiliary switch. In particular consideration given in the paper it was proposed to make another delay between auxiliary switch turn-off action and main switch turn-on action. This delay reduces secondary current before secondary rectifier turns off. That delay could be made for example by adaptive adjusting based on previous time period. Insertion of that kind of delay is optional and will certainly complicate the snubber. Simulation shows that if a flyback converter is working close to discontinues conduction mode that delay facilitates ZCS and ZVS for both secondary rectifier and primary main switch due to transformer magnetizing inductance energy gained during stage 4.

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