Optimisation and Simulation of RC Time Constants

in Snubber Circuits

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***Abstract*— Semiconductor devices are subjected to elevated levels of stresses when used at high voltage high current and temperature applications. This stress is mainly due to hard switching which is proportional to the switching frequency. This paper presents methods used to remove this energy to prevent expensive switch damage due to overheating and high dv/dt oscillations. In confirmation of the research title, the process in the determination of 'RC' in snubber circuits has been proven by OrCAD optimisation and presented.**

***Keywords*— Hard Switching, Input-Output Parameters, Simulation, Snubber Circuit (RC), Switching Frequency, Losses, TC Optimizations.**

I. Introduction

In the design of converters, power supplies etc., it is necessary to select components with optimum characteristics to ensure switching devices function within their Safe Operating Area (SOA). Failing such selection, there are indirect losses to consider due to manufacturing down time [1] and cost [10] of equipment replacement.

In practice the RC time constant can be a fraction of the switching cycle period T, or related to the transient period (t_{off}) of the switch at turn-off, which will allow the capacitor to charge (diverting the switch current) and discharge completely at turn-on [14] [15]. This energy if completely diverted to the capacitor will be equal to ½ CV^2 joules. Further analysis will be carried out to optimise the RC values for maximum transfer of the capacitor energy as heat dissipated in the resistor or transferred to the input for efficiency enhancement [3].

Methods to determine Time Constants are complex. Most articles recommend values based on experimental results (Rule of Thumb Method), by selecting the values of R and C that removes most of the switch energy at switch-off transition [4]. Other methods, employ simulation, algorithm tools and programs that require input parameters before the simulation begins[5]. Example of inputs are, initial values of R and C, voltage across the switch, load current, switching frequency and switching losses. These inputs are fed into a "simulation black-box" with a choice of output target conditions, i.e. minimum switch loss, optimum values for R and C and ideal switching frequency. The initial values of R and C will be determined by using the basic Rule of Thumb method, which will test various RC time constants until a minimum switch loss is obtained. The output of this process will provide the optimum design parameters for the protection circuit (see Fig.1) [1][2][3][4][5]. The methods to determine RC time constants are posted in the block diagram of Fig.2.

Determination of RC time constants at low frequency and high frequency applications will also be determined by simulation process. These results will enable correct design of over voltage protection circuits depending on the switching device selected and its operating frequency.

The RC time constants for the Turn-Off snubber circuits has been suggested to be a fraction of the switching device on/off period, i.e. T/2, T/3, T/5, T/10 and T/13, [6] [7] [8]. The requirement is that the capacitor must be charged during the switch off period and be discharged sufficiently during the switch on period, to be ready for the next off/on switching cycle. Other methods involve several simulations of the schematic circuit, with different values of R and C in the snubber circuit, until an optimum RC time constant is found. Fig. 2 provides some methods available involving critical circuit analysis [9]. In most Power Electronics research, the popular methods used are PSpice [11] and MATLAB. Due to the limited size of the paper set by UPEC, the description will focus on PSpice simulations.

II. Switching waveforms

Fig. 3, shows a standard voltage pulse switching waveform, which will be used to drive the MOSFET device in the test circuits to follow.

Fig. 4, shows a complete RC turn-off snubber circuit connected across the switching device. ESR (r1), is the capacitor Equivalent Series Resistance normally selected from the manufacturer's capacitor data sheet. During the turn-off transition, the capacitor via D2 and r_1 is required to divert the switch current and reduce the switch terminal voltage, ideally to zero volts. At turn-on, C, r_1 and R in the discharge circuit, dissipates the capacitor stored energy into R. It takes approximately five-time constants to fully charge a capacitor. However, the charge time of the capacitor will be determined by a fraction of the turn-off transition period (t_{off}) as suggested above and is discussed in the next section.

III. DETERMINATION OF SWITCHING DEVICE TURN-OFF PERIOD

A. *Manual determination of RC time constant for Snubber circuit using PSpice*

Fig. 5, shows two Buck converter circuits. Circuit A with a MOSFET switch without a snubber circuit. Circuit B with a MOSFET switch with a snubber circuit.

The first step in finding the RC time constant is to determine the transient switch off period (t_{off}) of the switching device. A PSpice simulation of circuit A was therefore carried out and (t_{off}) was measured in Fig. 6 to be 0.09µs. It was decided to choose a time constant of 20ns to be within the (t_{off}) period (i.e. < 0.09µs) [13].

After *several simulation* runs with combinations of C8 and R6, with fixed time constant of 20ns, the final values of C8=100n and R6=0.2Ω, were found. Voltage *differential* probes (green), current probe (red) and power probe (blue), required separate PSpice simulation runs. These simulations are shown in Fig. 6.

B. *Calculation of Switching Device Energy during t_{off}*

With no snubber circuit, switch energy during the switching period t_{off} = (673Wx 0.09 x 10^{-6})/2 Joules, (where VI = probe power value)

= 30.3 µJ

With snubber circuit, the switch energy is due to the 7.8W during the period measured as 0.000025ms

= 7.8W x 0.000025ms/2

= 0.0975 µJ

Switch energy during t_{off} = 6W x 1.3µs/2

= 3.9 µJ

The total energy, = 0.0975 µJ + 3.9 µJ = 3.9975 µJ

Reduction of switching energy,

= (30.3 – 3.9975)/30.3 x 100

= 86.8%

The above PSpice simulation, has demonstrated that although time consuming due to running several simulations, can result in finding effective RC time constant for the Turn-Off snubber circuit, which in this case has reduced the MOSFET switching energy by 86.8%

C. *Comparison of MOSFET Power level at turn-on and turn-off without protection*

Fig. 7, shows, the voltage, current and power traces for two complete cycles of T (100µs). The turn-on and turn-off periods, have equal mark/space ratio of 50 µs. Due to load current, the MOSFET power at start of turn-on, (3.5kW) is much greater that the power at start of turn-off, (0.65kW) since the load current at turn-off is zero. The only power at turn-off is due to the di/dt decay and dv/dt rise across the switch (hard switching).

D. *Load Power to determine TURN-ON snubber time constant*

i.e. Load power = turn-on power – turn-off power

= (3.5 - 0.65) kW

= 2.85 kW

This load power will be useful when calculating the time constant for a Turn-On snubber circuit, whose function is to reduce the MOSFET in-rush current at turn-on. (Not included in this paper).

E. *Ratio of RC/Transient period t_{off}*

Determination of the above ratio, which was effective in the reduction of the switch energy to zero level.

The turn-off period, t_{off}, = 0.09µs.

In Figure 5 B, RC time constant, τ = 0.2Ω x 100nF = 20ns

The ratio of, τ/t_{off} = (20 x 10^{-9}) / (0.09 x10^{-6}) = 0.22

Hence, RC time constant, τ = 0.22 x t_{off} ≈ 1/5 x t_{off}.

This result shows that by finding t_{off}, without snubber protection, the value of the snubber circuit 'RC' time constant can be calculated as (1/5 x t_{off}) [12].

Ratio of RC/Turn-Off period T/2

In Figure 5 B, RC time constant, τ = 20ns

The turn-off period, T/2 = 50µs

The ratio of, τ/(Turn-off) = (20 x 10^{-9}s) / (50 x10^{-6} s)
= (1/2.5) x 10^{-3} s
= 0.4x10^{-3} s

Hence, RC time constant, τ = 0.4x10^{-3} x Turn-Off period

Knowing the device switching frequency (mark/space), the RC time constant τ can be found from the above relationship.

Hence, the time constant of (C8=100n & R6=0.2Ω) = 50ns, can be determined by either the ratio of (1/5 x t_{off}) or

(0.4 x 10^{-3} x Turn-Off period, T/2), which resulted in an effective reduction of the switch energy by the snubber circuit.

IV. CALCULATION OF R AND C FOR SNUBBER CIRCUIT BY "AREA" METHOD

The RC product is in units of time and can conveniently be represented by the area of a rectangle as in Fig.8 .The object is to find the minimum values of R and C for a given area "A" in units of time.

The Steps in the procedure are: -

STEP

1. Area $A = C \times R$
2. Perimeter $P = 2C + 2R$ (1)

Reduce P for minimum A,

3. Minimum A $= X$
4. $C \times R = X$
5. Substitute for $C = X/R$ (2)
6. (2) in (1) $P = 2(X/R) + 2R$

   $P = 2R + 2XR^{-1}$ (3)
7. and, $P' = 2 - 2XR^{-2}$

   $= (2R^2 - 2X) / R^2$ (4)

There are two roots in (4), $(2R^2 - 2X)$ and R^2. The root in

$R^2 = 0$, which is not practical and is ignored. The critical value for R is found in,

8. i.e. $(2R^2 - 2X) = 0$, and $R = \sqrt{x}$ (5)
9. since $C \times R = X$, then $C = \sqrt{x}$ (6)

A. Confirmation of the Area method

The PSpice simulation of the circuit in Fig.5A, gives the (t_{off}) period to be 0.09 µs and will be used to calculate R and C using the result in above method.

Example

Let, $C R = X$ = 0.09µs, (switch-off transition period, t_{off})

And from (5) and (6), C & R = $\sqrt{x}$

Hence, C = 0.3µf, and R = 0.3Ω

The R and C component values were entered in the test Buck converter PSpice schematic in Fig.5B and simulated.

Fig. 9 shows the result of the PSpice simulation.

Since the period for the 10W is negligible, the energy will be ignored. The energy in the MOSFET during the measured turn-off transition of 4µs is,

= 4µs x ½ x 2W

= <u>4 µJ</u>

From section III B, the MOSFET switching energy without snubber circuit was 30.3µJ.

From this simulation, reduction of switching energy is,

= {(30.3 - 4)/30.3} x 100

= <u>86.8%</u>

This is reduction of the MOSFET switching energy, compares exactly to the 86.8% reduction figure in section III B above. This calculation Area method confirms the R and C values were equally effective in reducing the switch power loss. By changing the R and C to PARAMETER values with min/max ranges using PSpice Advance Analysis, the switch loss energy may be further reduced to the ideal zero value.

V. CALCULATION OF R AND C BY PARAMETRIC ANALYSIS IN PSPICE

This section will determine the optimum value of the RC time constant of the Snubber Circuit, based on changing a component to a global parameter with a minimum and maximum range. There will be several PSpice simulations, depending on the number of increments in the parameter range [16]. The capacitor value was parametised and the resistor value randomly adjusted to 0.288Ω (to be less than the 0.3 Ω in the Area example). In Fig.10, C11 was renamed as a variable capacitor{Cval}. C11 was swept from 0.2µf to 0.3µf, with 0.02µf increments, resulting in six iterations. Fig.11 and Fig.12 are the iteration results, with a final value for C = 0.3µf corresponding to the minimum power of 5W. The time constant of R=0.288Ω and C=0.3µf = 0.0864µs, is less than t_{off} = 0.09µs in section A. In Fig.11, examination of the peak of each power trace corresponds to a time value on the time axis. Hence, t_{off} = 0.09µs will correspond to a peak power value of 2W. Comparing the two power levels (2W & 5W and corresponding times), PSpice analysis would indicate that for a minimum switch loss, the RC time constant must not be less than a switch transition period (t_{off}) (when measured without snubber circuit connected). Further benefits could be expected if both R and C were simultaneously Paramatised.

VI. CONCLUSIONS

In this paper, critical time constants were determined by three methods, calculations involving several iterations in PSpice simulation, minimisation of 'RC' time constant by an Area method and the 'Parameter' method of sweeping through a range of C minimum to maximum values in PSpice analysis.

By limiting the value of the RC time constant within the transition switching period (t_{off}), the switching device loss energy was reduced from a no protection level to 86.8% with the snubber circuit connected. Further reduction of the switch energy is possible by parametizing both R and C in the snubber circuit.

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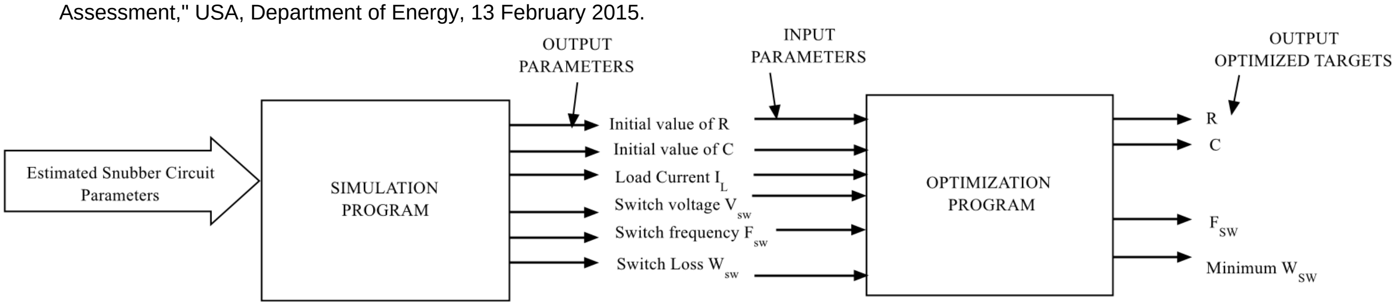

Fig.1: Simplified RC Time Constant Simulation/Optimization process

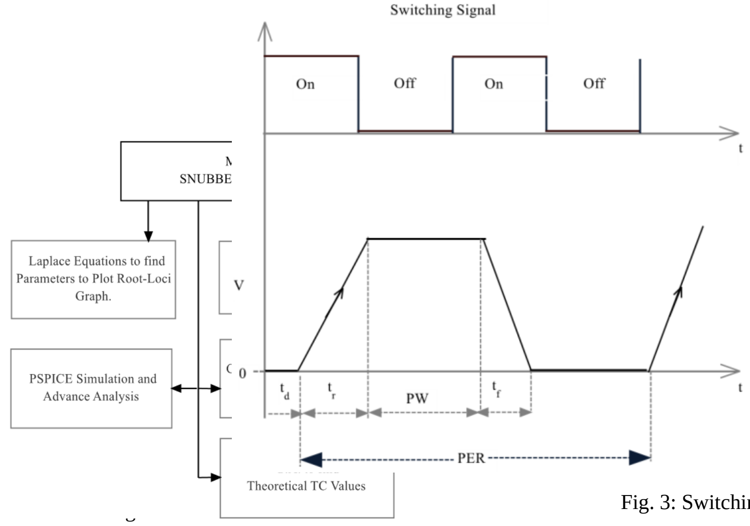

Fig. 3: Switching Waveform

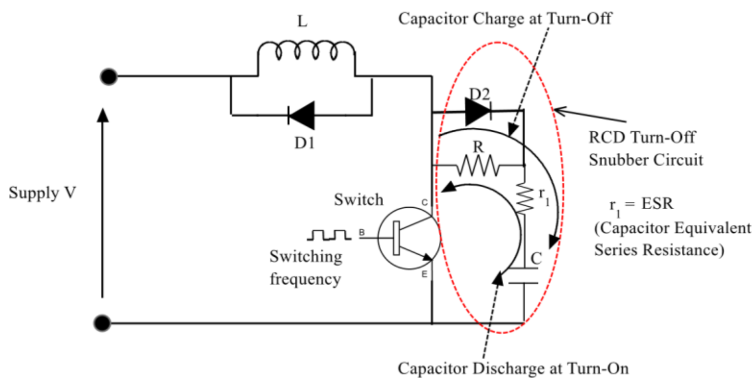

Fig. 4: Capacitor Charge and Discharge in RCD Snubber circuit

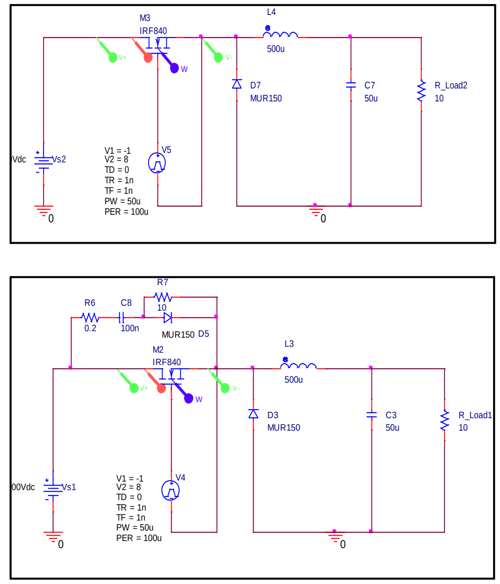

Figure 5-Buck Converter with a MOSFET switching device.
Without snubber (top) and with snubber circuit connected (bottom)

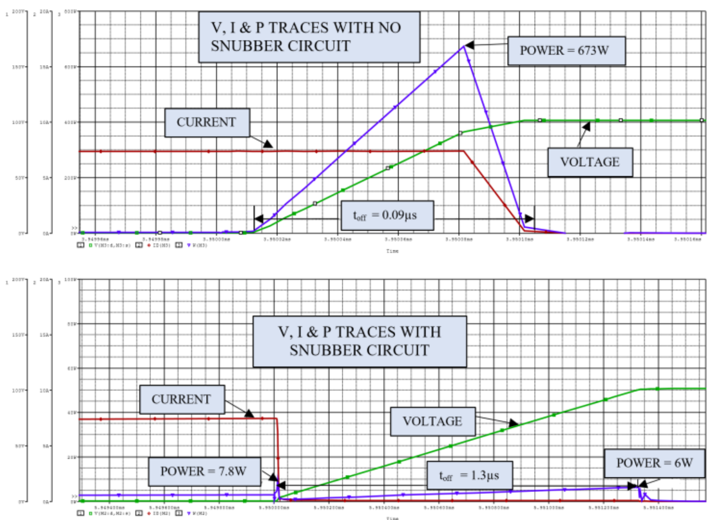

Fig. 6-Waveforms for Buck Converter
Top without snubber, bottom with snubber circuit

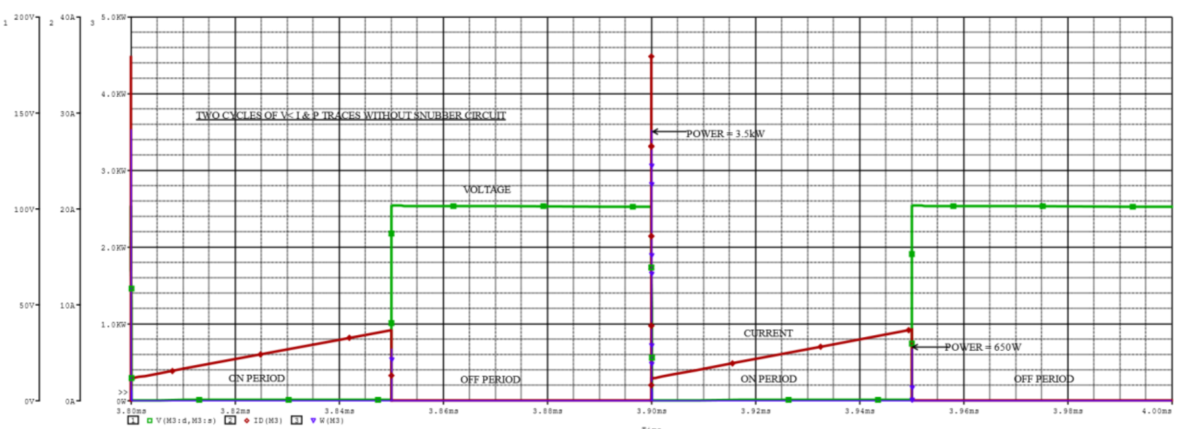

Fig. 7-Two cycles of V, I and P traces for Buck Converter without snubber circuit

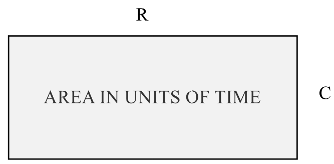

Fig. 8-R x C represented by a rectangle

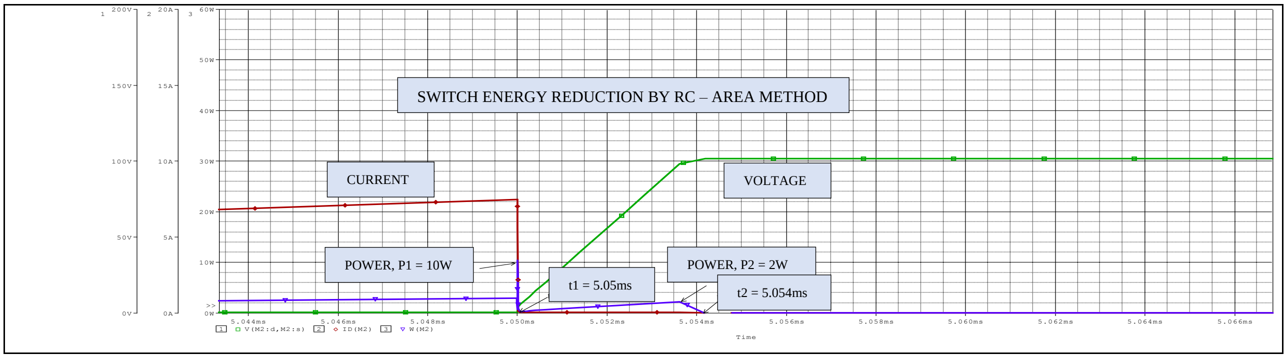

Fig. 9-Simulation of Switch Energy reduction by AREA Method, showing the Voltage, Current and Power Traces

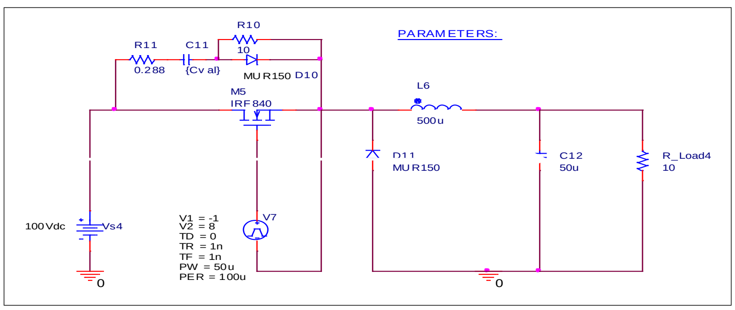

Fig. 10-Schematic to test the response of the snubber circuit on the MOSFET with a range of C11 from 0.2µf to 0.3µf, with increments of 0.02µ

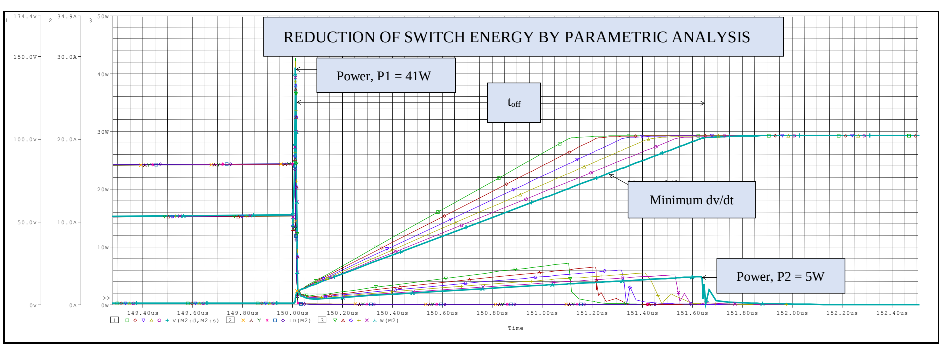

Fig. 11 -V, I and P traces (in groups of six) - Sweep of the snubber capacitor, from 0.2µf to 0.3µf in steps of 0.02µf, with R fixed at 0.288Ω

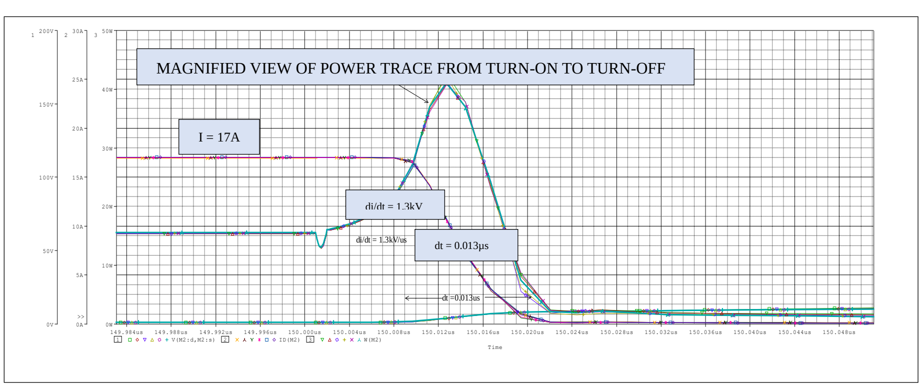

Fig. 12-Magnified view of the Peak power area in the switch of Fig.11