Modelling and Designing the RC Snubber Circuit for a Buck Converter and Testing its Effectiveness

Conference Paper · November 2016

DOI: 10.1109/IRSEC.2016.7984061

Ali Algaddafi
Sirte University

Modelling and Designing the RC Snubber Circuit for a Buck Converter and Testing its Effectiveness

Ali Algaddafi
Department of Electrical and Electronic Engineering
University of Sirte, Libya
alisirte@yahoo.com

Khalifa Elnaddab
School of Engineering at Cardiff University
Cardiff, CF24 3AA, UK
ElnaddabKA@Cardiff.ac.uk

Abstract — **The semiconductor power devices are the main core of all power electronic devices. Therefore, the protection of semiconductor devices and their operation at a safe level are required. Semiconductor power devices, resistors, and capacitors usually have parasitic inductances and capacitances. When a rapid switching transition occurs in the switching devices, it creates a noise, an electromagnetic interference and ringing, on the waveforms. These issues in power switching devices can be resolved by either replacing the switching device with another switch that has rated to exceed the stress or by using a series Resistor-Capacitor (RC) circuit to reduce the stresses to a safe level. The former solution increases the cost, while the snubber circuit, which is a simple RC circuit, is popular and is commonly used for any practical switching circuit, such as power converters, motor drivers, and power electronic devices. Although some works have been addressed in designing the RC snubber circuit, those studies are either based on simple work, or they involve very complex method with results that are often difficult to interpret.**

In this paper, therefore, we establish how to design an RC snubber circuit experimentally for a buck converter. The buck converter is modelled in PSpice software with and without the RC snubber circuit, where the comparison can be made. The model results show that the current across the switching device is reduced by the RC snubber circuit. In addition, the experimental results validate and verify the effectiveness of the RC circuit and eliminate the ringing and the noises.

Keywords—RC snubber circuit, the ringing frequency, voltage and current spikes, Electromagnetic interference, DC buck converter.

I. Introduction

Switching devices are the heart of power electronic equipment and are utilised in many applications, e.g., renewable energy resources (solar system, wind power) and drive machines. Therefore, the switches, which include the Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFET), an Insulated-Gate Bipolar Transistor (IGBT), Thyristor, and a transistor, should have protection and should operate at a safe level of stress. Although the snubber circuit is not a fundamental part of a power electronic converter circuit, it is utilised to suppress the high-frequency oscillation related to the reverse recovery effect in a power semiconductor application. A snubber is a damping circuit which is placed across switching devices, both for protection and to enhance the performance of the system. The damping circuit has many advantages as follows [1, 2]:

1-eliminates the voltage and current spikes

2-reduces the Electromagnetic Interference (EMI) by damping the voltage and current ringing

3-limits dI/dt or dv/dt

4-creates the safe operating area for the load line

5-reduces the losses of the switching devices

6-reduces the heat of the switches

There are many types of the snubber, such as the Resister-Capacitor (RC) damping circuit and the Resistor-Capacitor-Diode (RCD) clamps [1]. In RCD, the effective value of the resistor is essentially zero during the charge capacitor due to the diode across the resistor, which is a main problem of the RCD circuit. The RC snubber circuit is simple and is needed for all snubber circuits;it is only this circuit that is considered in this paper.

The low-cost of the RC snubber circuit meant it was proposed by Thong for a bifilar wound single-phase AC inverter [3]. The leakage inductance caused a voltage spike across the switching devices that were at least twice the supply voltage. Although Thong reduced the capacitor value and the total losses of power in the snubber resistor, the two resistors were used, and thus the result is difficult to interpret.

The design of the RC snubber for the transistor was presented in [4] utilising the root locus method. Although, the effectiveness of this method gave a good result, the total loss was not minimised, and the transistor and diode were assumed to be short circuits in a state of ON.

This paper presents the modelling and designing of an RC snubber circuit for a buck converter and tests its effectiveness. Section II describes the system configuration, which includes analysis of the transition switches and the development of the RC damping circuit within the DC buck converter. Section III shows the experimental verifications, which involve the experimental setup, and discusses the experimental results. The final section draws the conclusion and presents possibilities for future works.

II. SYSTEM DESCRIPTION AND CONFIGURATION

A. *Analysing the transition switches*

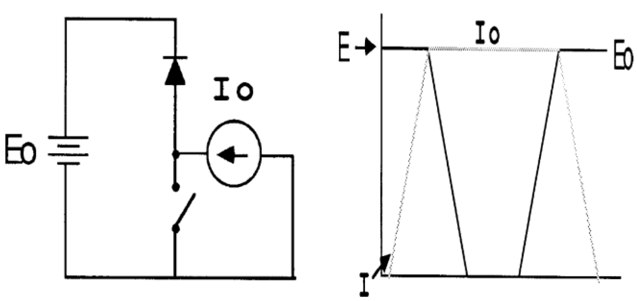
The designs of some converters neglect the impact of the ringing in the switch devices and operate without the snubber circuit. This leads to the voltage on the drain of the MOSFET being exceeded. Consequently, an avalanche breakdown and failure of the devices may occur. In addition, the high frequency will be radiated throughout the load and the

978-1-5090-5713-9/16/$31.00 ©2016 IEEE

electronic system, which creates noise issues. Therefore, the RC snubber, the RCD clamp, or a combination of both must be used to reduce the stress and the noise.

To introduce the motivation for utilising the RC snubber circuit in the DC buck converter, it is important to understand the nature of the switching devices. This circuit can be used in different power converters, such as DC/DC converters [5] (buck, boost, buck-boost and others), DC/AC inverters, motor drives [3], and other devices. The behaviours of those power converters demonstrate the same switches. This leads to an analysis of one RC snubber circuit for one converter, for example. The results can then be generalised to other power electronic circuits. Parasitic inductances and capacitances during rapid switching transition, which are unavoidable, may burn the switches and create a lot of noise and ringing in the waveforms. Therefore, the RC snubber is the primary solution to tackle those noises, the ringing, and the EMI. The performance of the circuit during the transition at the time of the switch is analysed to make it possible to understand the nature and behaviours of the switching devices.

For example, in the boost converter, by changing the inductor current to the source current and changing the output voltage across the capacitor by the source voltage, the waveforms of voltage and current are given as shown in Fig 1.



(A) Equivalent circuit (B) Waveforms across the switch

Fig. 1. Analysing the boost converter in transition time as in (A) and (B) [1].

When the switch turns off, the current goes to the load (E_O) through the diode. As the switch turns on, the current will gradually transfer from the diode to the switch, while the switch voltage will remain at E_O. Once all of the current has been transferred to the switch, the switch voltage commences to fall and vice versa. As the switch turns off, the switch voltage rises to E_O, while the current remains at I_O. Once the switch voltage has reached E_O, the current starts to fall and transfers to the load through the diode [1]. This analysis helps to simplify the analysis of the behaviour of the hard switch in power electronics.

B. Development of the Buck Converter in PSpice

A buck converter is considered as a simple method for reducing the Direct Current Power Supply (DCPS) voltage, which involves decreasing the output voltage and increasing the current. If the buck converter has a large voltage ripple, it may be reduced by using a large capacitor. PSpice software was used to test the buck converter, as described in Fig 2. The PSpice simulation presents results close to the practical results when the physical parameters are utilised in PSpice. The physical parameters of the buck converter were employed in the PSpice model in order to reduce the modelling error. Some electronic elements are not included in the PSpice library, and thus, these have had to be replaced by other elements, which include, but are not limited to, the MOSFET (IXFN32N120) [8] and the Schottky diode (DSS 17-06CR) [9]. The optimal value of the parameters of the buck converter is selected according to Eqs. 1, 2 and 3 [3, 6]:

$$\frac{V_{out}}{V_{in}} = D \tag{1}$$

$$\mathrm{L} = \frac{(\mathrm{V_{in}} - \mathrm{V_{out}}) * \mathrm{t_{on}}}{\Delta \mathrm{I_l}} \tag{2}$$

$$\mathrm{C} = \frac{(\mathrm{V_{in}} - \mathrm{V_{out}}) * (\mathrm{t_{on}})^2}{2 * \mathrm{L} * \Delta \mathrm{V}} \tag{3}$$

Where: V_{out} is the output voltage, V_{in} is the input voltage, D is the duty cycle, L is the inductor of the buck converter, $\mathrm{t_{on}}$ is the switching on, $\Delta\mathrm{I_l}$ is the output current ripple of the buck converter, C is the capacitor of the buck converter, and ΔV is the output voltage ripple of the buck converter. The inductor should be selected to operate in a continuous conduction mode, where the inductor current during the commutation cycle should never fall to zero [7]. Thus, the minimum inductor was selected when $\mathrm{V_{out}} = 0$.

Notice that the values of the capacitor and inductor may change according to available elements in the laboratory; these are listed in Table I.

Table I. Selection parameters of buck converter [6].

No	Parameters	Symbol	Values
1	Switching frequency	F_{sw}	25KHz
2	Inductor	L	1mH
3	Capacitor	C	1uF
4	Parasitic resistance of L	r_L	0.4Ω
5	Parasitic resistance of C	r_C	2.06Ω

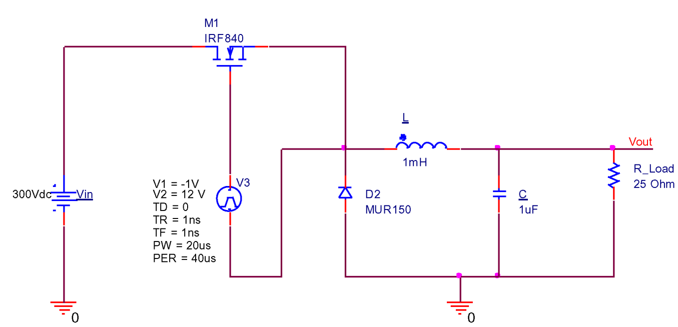


Fig. 2. Schematic diagram of a buck converter circuit in PSpice.

In this paper, the buck converter is designed with the RC snubber circuit in order to implement a design for the Photovoltaic Array Emulator (PVAE).

C. Development the RC Damping Circuit

The snubber circuit is defined as a resistor and a capacitor connected in series across a switch. It is utilised to suppress the voltage and current spike in the device. The voltage spike on the drain of the MOSFET may cause failures and may damage the switch. To overcome this problem, the RC snubber can be employed. The snubber circuit is used to limit the overvoltage and overcurrent [1, 2]. Two equations, (4) and (5), can be utilised to design the RC snubber circuit, as presented by Vaculik [2]:

$$\zeta = \left(\frac{1}{2R_S}\right)\sqrt{\frac{l_{lk}}{c_{lk}}} \tag{4}$$

$$f_{RING} = \frac{1}{2 * \pi * C_S * R_S} \tag{5}$$

where ζ is the damping circuit, l_{lk} is the total stray inductance, c_{lk} is the parasitic capacitance of the buck converter, R_S and C_S are the RC snubber circuit values that are required, and f_{RING} is the ringing frequency of the circuit. Three elements must be taken into account when the RC snubber is designed, as follows [2]:

1-C_{lk} is the parasitic capacitances due to output capacitance (C_{oss}) of the switch and diode capacitance. These parasitic capacitances can be obtained from the data sheet of components.

2-L_{lk} is the leakage inductance and is sometimes called the total stray inductance. This includes the cable inductance, lead inductance, connection inductance, and device package inductance. These are difficult to obtain without building the circuit experimentally, hence the reason for designing the RC snubber circuit in the laboratory, where the model can be challenged to give the optimal values of the RC snubber circuit.

3-F_{ring} is the ringing frequency, which can be obtained from the experimental test.

The RC snubber circuit is called a damping circuit because it depends on the damping ζ . Generally, in modern control engineering, the damping ζ is classified into three cases as in [10]:

ζ <1 is called under damping

ζ =1 is called critical damping

ζ >:1 is called overdamping.

The snubber resistor is used so it is effective at the ringing frequency while the snubber capacitor is utilised to reduce the dissipation of the switching frequency [2]

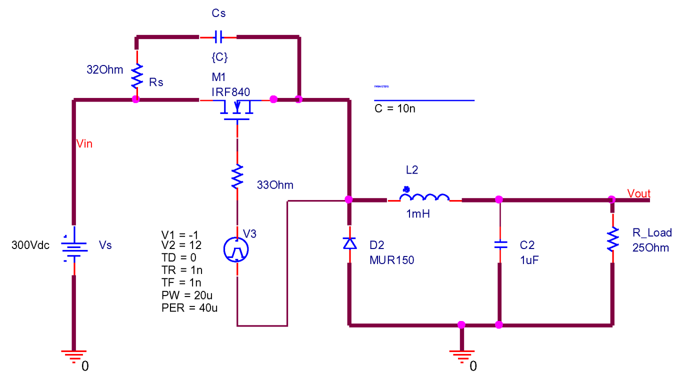
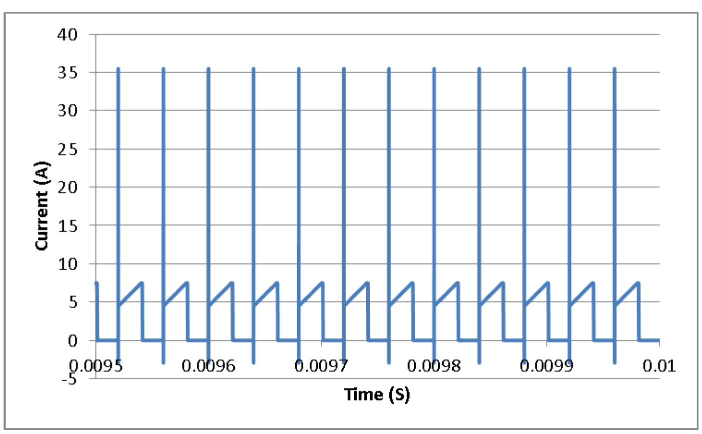


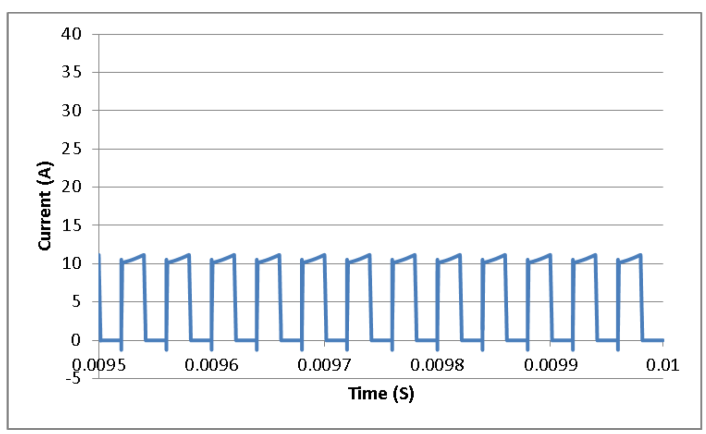
Fig. 3. RC snubber circuit with the buck converter circuit in PSpice

The RC snubber circuit was employed, as illustrated in Fig 3. The ringing frequency on the switch was not noticed in the modelling results, which made it challenging to calculate the value of the snubber circuit. Therefore, the sweep parameter available within PSpice was used to estimate the capacitor's value, which varied between 10 nF and 1.510 µF, with an increment of 500 nF. The selected value of the snubber capacitor was 1.5 µF.

Fig 4 (A) reveals a current spike passing through the drain of the MOSFET without an RC snubber circuit, while Fig 4 (B) also includes an RC snubber circuit. The voltage and current spike may be caused by the stray inductor and parasitic elements in the buck converter. It can be seen that the RC snubber circuit eliminated the current spike of the buck converter, which will thus protect the MOSFET.



(A) Without RC snubber circuit



(B) With RC snubber circuit

Fig. 4. The input current spike at the drain MOSFET of the buck converter, as seen in (A) and (B).

The output voltage and current of the buck converter are observed when the RC snubber circuit is connected, to ensure that the buck converter provides acceptable results with the RC snubber circuit, as shown in Fig 5.

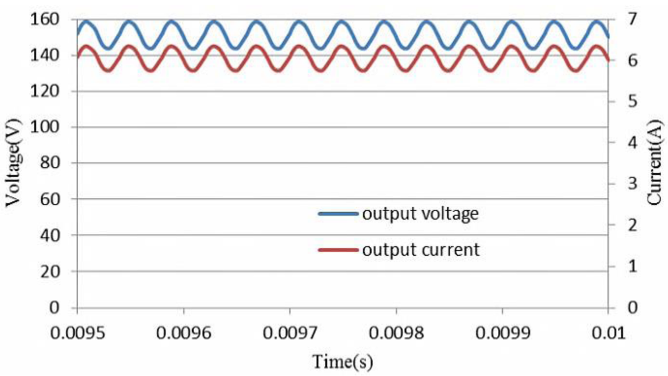


Fig. 5. Output voltage and current of the buck converter when the RC snubber was connected

The efficiency of the buck converter without the RC snubber was 98%, while with the RC snubber, it was found to be 62.5%. The MOSFET of the buck converter requires a snubber circuit, with the RC snubber circuit depending on the type of MOSFET. Therefore, only the experiments to build the buck converter and design the RC snubber circuit are presented in this paper, while combining all of the elements of the PVAE will be considered in other publications.

III. EXPERIMENTAL VERIFICATION

A. Experimental Setup

The experimental setup combined the different parameters of the buck converter given in Table I, as shown in Fig 6. The buck converter was controlled by using a function generator device. In addition, the drive circuit was supplied by the voltage and was connected to the gate drive of the MOSFET.

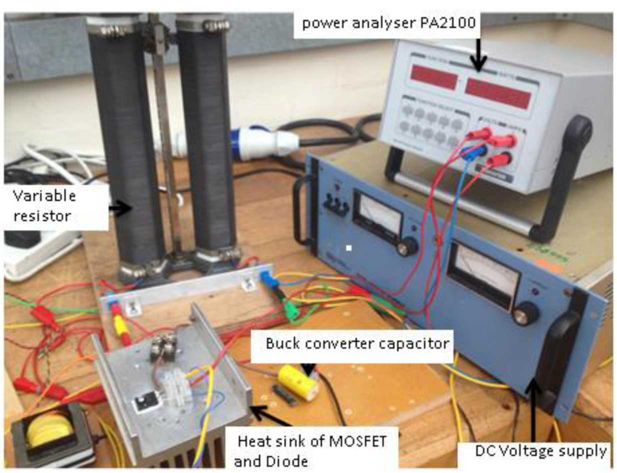


Fig. 6. The power circuit of a buck converter with RC snubber circuit.

The voltage and current across the MOSFET were observed by using an oscilloscope (Tektronix MDO3024).

B. Experimental Results

A buck converter was built experimentally according to the parameters in Table I. Fig 7 illustrates the measured voltage across the MOSFET and the current through the MOSFET.

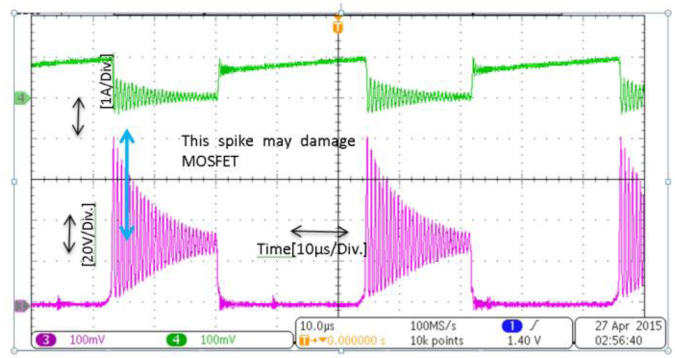


Fig. 7. The voltage of the MOSFET (in purple) and current (in green) at 30 V.

It is clear that the buck converter experienced a large oscillation of voltage and current. Furthermore, the voltage and the current experienced a spike. The voltage on the MOSFET is more than twice the input voltage, as can be seen in Fig.7, which could damage the MOSFET when the high voltage is applied by DCPS. Therefore, in order to overcome this problem, the RC snubber circuit was connected in parallel to the MOSFET after the design was adjusted as follows. The ringing frequency was measured as in Fig. 8, and equation (4) was used to determine the R_S value, while equation (5) was utilised to determine the value of the C_S of the snubber circuit. The oscillation frequency was measured at 1.5 MHz (640 nF), after the time domain had been expanded from the 10 µs/ division to the 2 µs/ division, as presented in Fig 8.

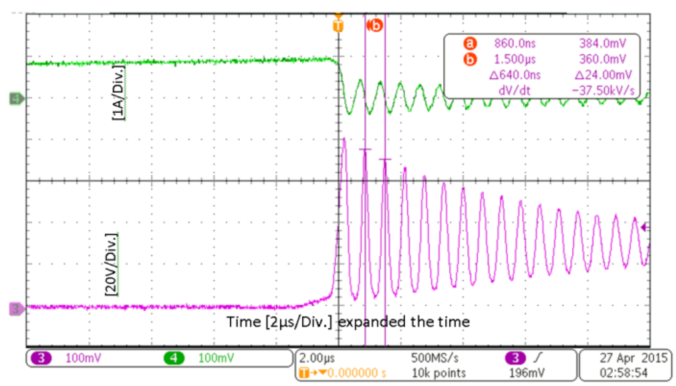


Fig. 8. Estimation of the ringing frequency of the buck converter at the input of 30 V.

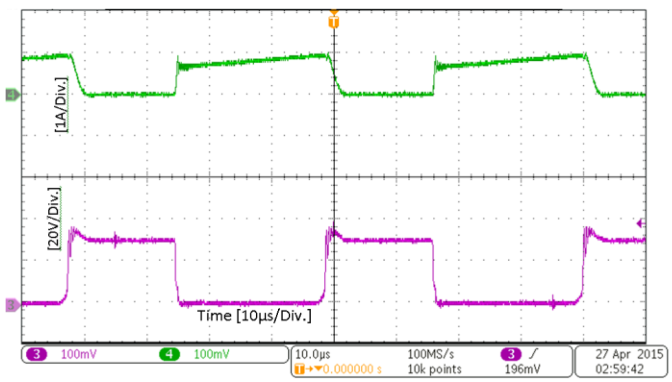


Fig. 9. The voltage of MOSFET and the input current when the RC snubber circuit was connected to the input of 30 V.

The values of the snubber resistor and capacitor were found to be 22 Ω and 470 nF, respectively. If Fig 7 and Fig 9 are compared, Fig 9 shows a low spike and is thus safer to use with the MOSFET switch.

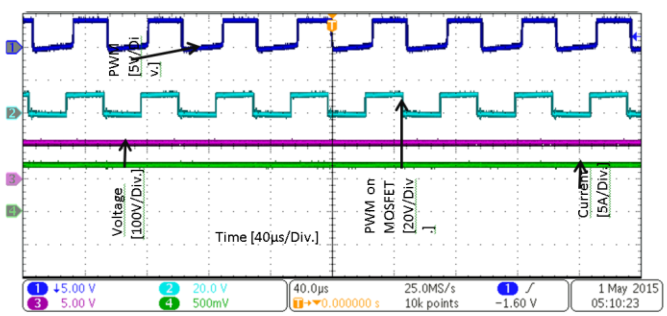


Fig. 10. Experimental measurements of the buck converter at input voltage=300V.

Fig 10 shows the output voltage and the current of a buck converter with the designed RC snubber circuit. Not only are the voltage and the current across the MOSFET measured, but also, the output voltage and current of the buck converter are measured to ensure the best performance of all the circuits. The output voltage is constant, as shown in Fig 11.

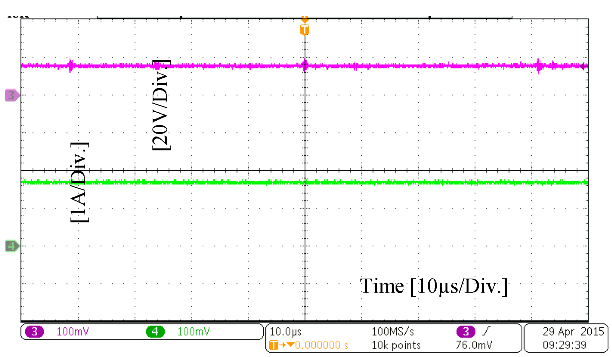


Fig. 11. Both the output current in green (4) and the voltage in purple (3) at Vin=30V.

The ripple (AC components) of the output voltage and the current of the buck converter, when the RC damping circuit is used, are observed, as shown in Fig. 12. It can be seen that the AC coupling waveforms of the output voltage and current are very low. This verifies the effectiveness of the RC snubber circuit.

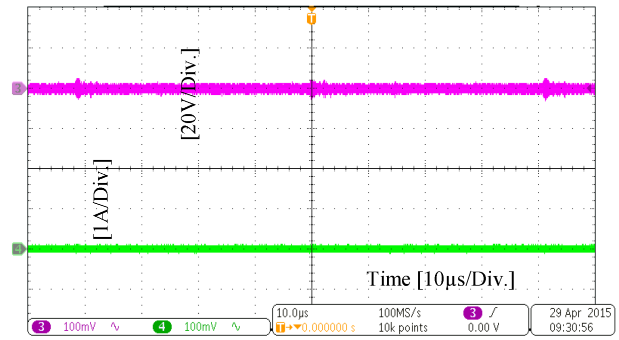


Fig. 12. Both the output current in green (4) and the voltage in purple (3) at Vin=30V.

The voltage on the MOSFET gives acceptable results where the spike is omitted. Besides this, the ringing is eliminated. Therefore, this circuit is ready for further investigation and it can be used to build the PVAE and can be combined with the other elements, as in [6, 11].

CONCLUSION

Many engineering designers ignore the impact of the ringing on the metal–oxide–semiconductor field-effect transistor (MOSFET) switching devices; this causes the voltage across the device to rise until an avalanche breakdown occurs. This is acceptable up to a normal rating of the MOSFET devices. However, in an Insulated-Gate Bipolar Transistor (IGBT), switches cannot tolerate a voltage overshoot that exceeds the IGBT rated voltage. Therefore, the RC circuit is a primary tool to eliminate or greatly reduce all of this type of noises. Therefore, the series RC damping network is needed and is very commonly used. Even when the other snubber circuits, such as the RCD snubbers and energy recovery snubbers, are used, they require the RC snubber circuit.

We modelled the buck converter and studied the impact of the RC snubber circuit on the performance of the switching of the buck converter. Since the RC snubber circuit reduces the current spike through the switch, this explains the importance of the RC snubber circuit in power electronic converters. Experimental work is conducted with a low voltage for safety reasons and to avoid damaging the power electronic devices. It has been established that the ringing frequency can be easily estimated in the laboratory. Then, the optimal value of the snubber resistor and the capacitor can be determined. In addition, the buck converter was tested with a high DC power supply voltage of around 300 V, and it was found to be safe meaning it is possible to continue with the experimentation to develop the Photovoltaic Array Emulator. The RC damping circuits reduce the voltage spike across the MOSFET to 67.5% of the spike voltage. However, the high power losses in the snubber resistor show that this RC snubber circuit is not suitable for the high-efficiency circuit. Therefore, as part of future work, the RCD snubber circuit will be considered.

ACKNOWLEDGEMENT

The experimental work presented in this paper was conducted at the Department of Engineering, University of Leicester, UK. I would like to offer my sincerest thanks to the Libyan cultural affairs in London and the Higher Education Ministry in Libya for their sponsorship.

REFERENCES

[1] R. Severns and E. Reduce, "Design of snubbers for power circuits", International Rectifier Corporation, 2009.

[2] P. Vaculik, "The Experience with SiC MOSFET and Buck Converter Snubber Design", World Academy of Science, Engineering and Technology, London, 2014.

[3] N. Mohan et al. “Power Electronics: Converters, Applications, and Design” John Wiley and Sons, 2003.

[4] W. K. Thong and C. Pollock, "A novel low-cost RC snubber", Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE, pp. 1743-1748 vol.3, 2001.

[5] K. Harada and T. Ninomiya, "Optimum design of RC snubbers for switching regulators", Aerospace and Electronic Systems, IEEE Transactions, pp. 209-218, 1979.

[6] A. Algaddafi et al. "An Analogue Computation based Photovoltaic Emulator for realistic Inverter Testing", The Third International Conference on Energy Engineering (ICEE-2015), 2015.

[7] A. Gadaffi et al. "Impact of PV Array Emulator on Power Quality of PV Inverter Compared to a Real PV Array", 3rd International Renewable and Sustainable Energy Conference (IRSEC'15), December 10-13, 2015, Marrakech & Ouarzazate, Morocco, IEEE Conference, 2015.

[8] Technical data of power MOSFET IXFN 32N120, available: "http://pdf.datasheetcatalog.com/datasheet2/b/0fyxf44f7jh77zwtoi0146af003y.pdf", accessed: [02/05/2016].

[9] Datasheet of Schottky diode of DSS 17-06CR, available: "http://www.farnell.com/datasheets/123707.pdf", accessed: [02/05/2016].

[10] D. Roy Choudhury, “Modern Control Engineering”, PHI Learning Pvt. Ltd., 2005.

[11] M. C. Di Piazza and G. Vitale, “Photovoltaic Sources: Modeling and Emulation” Springer London, 2012.