Impact of Variable Switching Frequency over Power Loss on Converter Topologies

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ABSTRACT
This paper compares different topologies of DC-DC converters for levels of mitigation of EMI using a RCD snubber for each. This paper proposes the design and simulation of a Buck, Cuk and the Boost converter using the software PSPICE. The circuit was constructed on PSPICE and the output voltage of the converter is simulated for different switching frequency. The simulated output was then studied for different switching frequencies keeping duty cycle constant, and EMI was found in the output due to switching of the MOSFET. In order to minimize this interference a RCD snubber circuit was designed in PSPICE across the MOSFET of the converter. The output and simulations of these three topologies were then studied in comparison to the output of these converters without snubber circuit.

1. INTRODUCTION
All power electronics equipments generate and emit unwanted electrical signals (EMI noise) that can lead to performance degradation of itself and other nearby electrical/electronic equipments. They generate high frequency conducted and radiated EMI noise and draw distorted line currents due to the sharp edges of the switching waveforms with high dv/dt. The different topologies that are used for the production of SMPS and other biomedical instruments have more stringent EMC regulations. The ever increasing use of off-line power supplies that have taken place over the years has led to the adoption of standards in order to achieve an adequate harmonic performance. These standards contain regulations for low order harmonic content (current distortion, e.g. IEC555-2) and high-order harmonics (EMI, Electro Magnetic Interference). The most restrictive commercial standard concerned with conducted EMI is the VDE0871. This standard specifies the maximum allowable conducted EMI generated by a piece of equipment. Meanwhile, the requirements for measuring apparatus and measurement methods are outlined by CISPR Publication 16. This publication states that the bandwidth of measurement in the range from l0kHz to 150 kHz is 200Hz. On the other hand, this bandwidth is 9 kHz for frequency ranging from 150 kHz to 30MHz. This change in the bandwidth of measurement affects strongly the EM1 performance.

2. ELECTROMAGNETIC INTERFERENCE
The switches with the high dv/dt and di/dt switching slopes are the main sources of EMI. High rates of dv/dt and parasitic capacitors to the ground are the reasons for common mode interference. Electromagnetic Interference (EMI) is an unwanted disturbance that affects an electrical circuit due to conducted EMI emission is interference that propagates through the metal conductors and cables. The interference sources are coupled onto the power cable to the equipment. In addition the interference may be coupled inductively or capacitively from another cable to the power cable. Conducted EMI emission is composed of two components commonly known as the differential mode and the common mode noise.
Conducted noise consists of two categories

2.1. Differential Mode Noise: It is measured between each power line and ground. Differential mode is due to magnetic coupling. Differential Mode noise attempts to dissipate its energy along any path from line to neutral. The transmission of the differential mode noise is through the input line to the utility system and through the DC network to the load on the power converter. Differential mode noise is present on both the input and output lines.

2.2. Common Mode Noise: It is measured between Line and ground. Common mode noise is due to stray capacitance. The transmission of common mode noise is entirely through parasitic or stray capacitors and stray electrical and magnetic fields. Common mode noise is present on both input and the common mode current flows into the parasitic capacitors between the power converter components and the protection earth. Since the common mode currents share most of their paths with other equipment, the level of EM1 emission from them is usually higher than that from the differential mode currents.

For this research, the effect of snubber circuit in the power loss reduction is analyzed for different switching frequency of Buck, Boost and Cuk converter.

3. PSPICE SIMULATION CIRCUIT

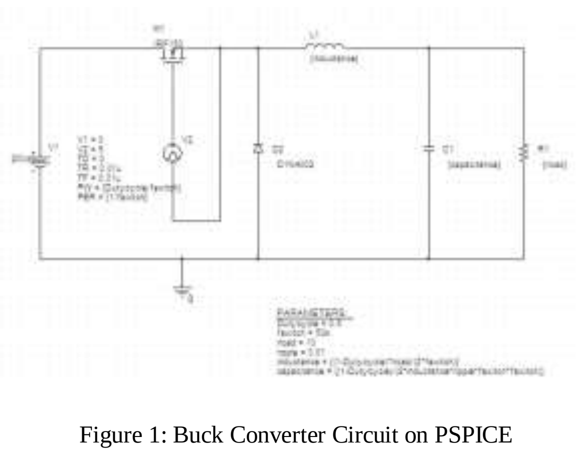

Figure 1: Buck Converter Circuit on PSPICE

Figure 1 shows the simulation circuit of Buck converter in PSPICE. To design a converter the value of inductor and capacitor should be calculated, and the MOSFET and diode need to be selected. In order to do this, the switching frequency, duty cycle and the load resistance should be known.

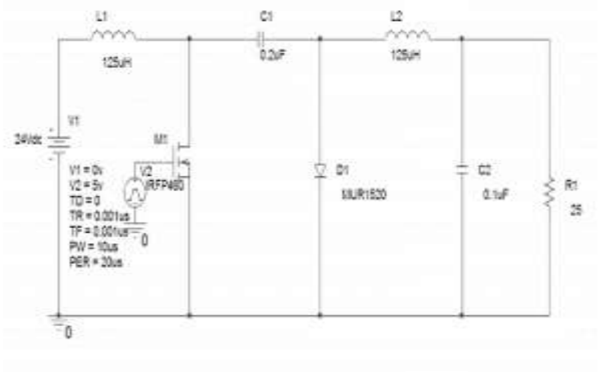

Figure 2. Simulation circuit of Cuk converter in PSPICE.

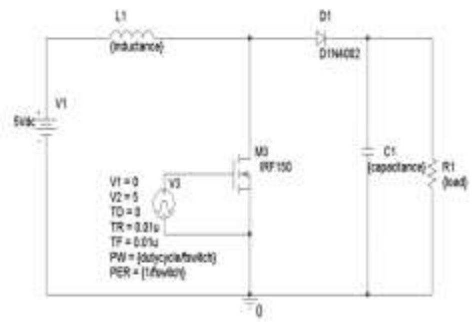

Figure 3.Simulation circuit of Boost converter in PSPICE.

4. SNUBBER CIRCUIT

The application of DC-DC converters appear in large numbers. Switching losses are high due to operation of the converters in hard switching mode. [1], [3] and [4]. The converter topologies could be realized as chip versions. For these advanced technologies the power losses must be properly evaluated and measures should be taken to reduce the losses effectively. The snubber circuits are usually placed in the converter structure to adjust the turn-on and turn-off losses. The switching-on snubber circuit is connected in series to limit the *di/dt* at turn-on. The switching-off snubber circuit is connected in parallel to limit the *dv/dt* at turn-off.
The purpose of using Snubber circuits is to

- Limit rate of rise of voltage across a switching device
- Limit rate of rise of current flowing through a switching device
- Modify the switching trajectory
- Reduce EMI

4.1. RCD Snubber circuit on Cuk Converter

The Cuk converter like all other hard-switched converters faces the problem of Electromagnetic Interference (EMI). In order to reduce the interference and hence increase the efficiency of the Ćuk converter a snubber circuit is applied to the MOSFET. A RCD Snubber is used on the MOSFET, where the values of capacitor C and resistor R are determined by the formulae that follow-

- $$C = \frac{I_d t_f}{2V_{ds}}$$

Where,

t_f stands for Fall Time of the MOSFET,

V_{ds} stands for Drain to Source Voltage,

I_d stands for Drain Current.

The value of C which is determined is then used to calculate the value of resistor R as given below-

- $$R = \frac{\tau}{C}$$

Where τ stands for discharge time.

Here it is known that

- t_f =100 ns;
- V_{ds} =100 V;
- I_d =12.318*1.1= 13.55 A

Hence capacitance C= 6.75 nf.

Discharge time= 35 ns

Hence resistance R= 5.185= 5 ohms (approx)

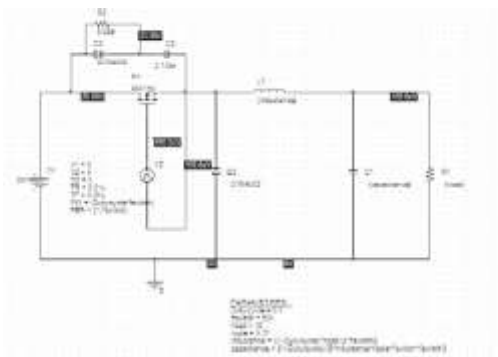

Figure 4: Buck Converter with snubber circuit

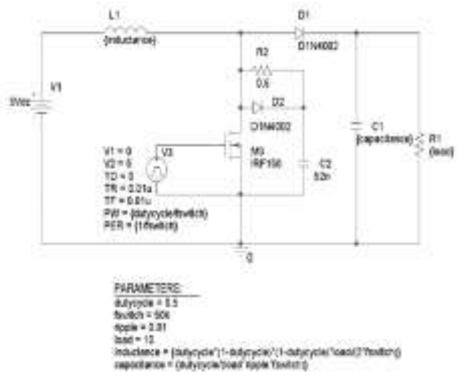

Figure 5: Boost Converter with snubber circuit

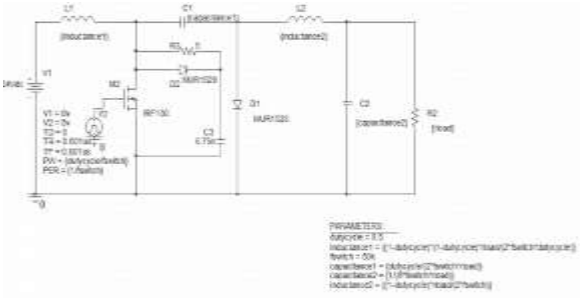

Figure 6**:** Cuk Converter with snubber circuit

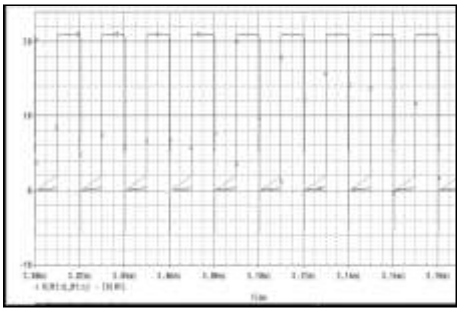

Figure 7: Voltage across drain and source of MOSFET and current across drain (Buck Converter)

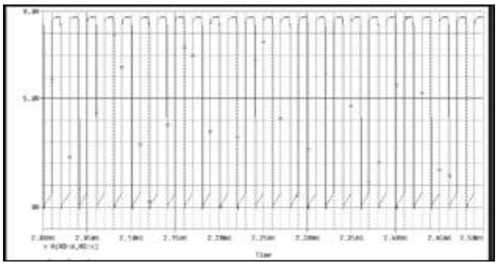

Figure 8: Voltage across drain source of the MOSFET (Boost Converter) without snubber circuit.

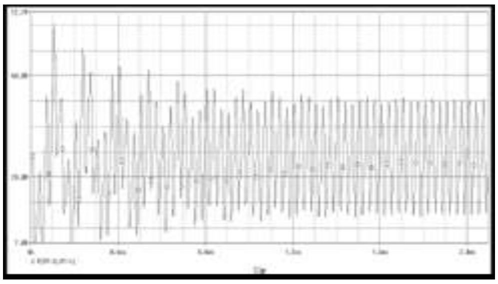

Figure 9: V_d for 30MHz without snubber circuit

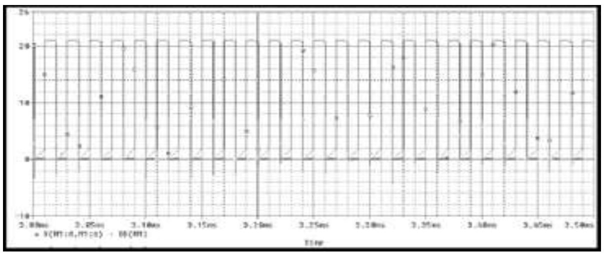

Figure 10: Voltage across drain and source of MOSFET and current across drain with snubber (Buck Converter)

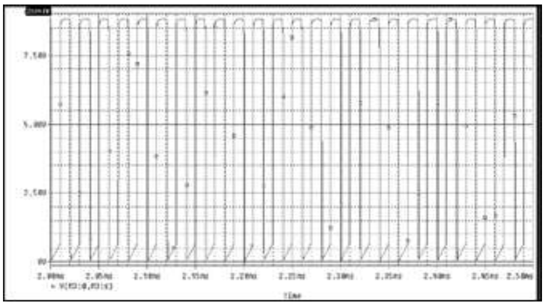

Figure 11: Voltage across drain source of the MOSFET (Boost Converter) with snubber.

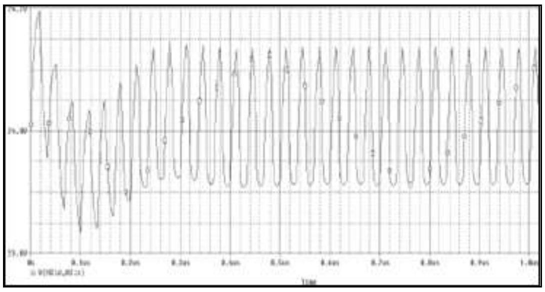

Figure 12: V_d for 30MHz with snubber circuit
(Cuk Converter)

Table 1. Buck Converter without Snubber

Frequency	I_d (A)	V_{ds} (V)	P_{ds} (W)	V_L (V)	I_L (A)	I_o (A)	V_o (V)
9 kHz	7.2984	21.26	151.328	20.014	7.2986	1.3143	13.143
50 kHz	7.2092	21.182	150.379	20.057	6.0391	1.0031	10.031
100 kHz	7.2086	21.131	150.495	20.057	4.9632	0.892837	8.9284
500 kHz	7.2015	21.02	149.184	19.973	3.5724	0.782147	7.8215
1 MHz	7.1909	20.975	148.723	19.870	3.4404	0.712936	7.1294
3 MHz	6.4641	20.861	132.302	19.338	2.3272	0.529231	5.2923
6 MHz	3.2683	20.72	66.991	8.7438	0.796004	0.259758	2.5977
9 MHz	1.8769	20.669	38.779	5.8675	0.576877	0.210212	2.1021
12 MHz	1.6146	20.64	33.104	4.5827	0.520069	0.219136	2.1911
15 MHz	1.3256	20.619	27.804	3.7741	0.562123	0.290454	2.9046
18 MHz	1.3424	20.604	27.596	3.0054	0.702499	0.500954	5.0096
21 MHz	1.4145	20.568	28.36	2.9043	0.937609	0.770295	7.7029
24 MHz	1.4016	20.508	28.604	2.803	1.2612	1.1441	11.441
27 MHz	1.8673	20.337	31.981	2.6914	1.8628	1.6711	15.711
30 MHz	2.2536	20.326	37.611	2.7236	2.2001	1.3245	13.245

Table 2. Buck converter With snubber

Frequency	I_d (A)	V_d (V)	P_d (W)	V_L (V)	I_L (A)	I_c (A)	V_o (V)
9 kHz	7.2775	21.256	150.297	19.997	7.2891	13.121	1.3121
50 kHz	7.1956	20.959	149.978	19.994	6.1153	10.132	1.0132
100kHz	7.165	21.136	149.606	19.991	5.0766	8.9542	0.895423
500 kHz	7.16	21.019	148.505	19.916	3.6539	7.7957	0.779571
1 MHz	7.1415	20.973	147.623	19.837	3.4013	7.2101	0.721013
3 MHz	6.452	20.853	132.408	18.787	2.2096	5.6358	0.563579
6 MHz	3.2343	20.719	66.026	6.9026	0.847337	3.2539	0.325394
9 MHz	2.0007	20.661	40.958	4.21	0.587977	2.8702	0.287019
12 MHz	1.4834	20.629	30.435	3.1979	0.542261	3.2363	0.323625
15 MHz	1.378	20.605	28.18	2.683	0.569206	4.0804	0.408036
18 MHz	1.3222	20.574	26.976	2.5101	0.693222	5.745	0.574502
21 MHz	1.2434	20.522	25.402	2.3937	0.939161	8.3513	0.835129
24 MHz	1.3984	20.224	26.394	2.351	1.2678	11.822	1.1822
27 MHz	1.8934	20.204	32.59	2.4721	1.803	16.806	1.6806
30 MHz	2.2281	20.202	36.364	2.5988	2.1875	19.158	1.9158

Table 3. Boost converter Without snubber

f_{switch}	V_L (V)	I_L (A)	V_{DS} (V)	I_{DS} (A)	$V_{DS}I_{DS}$ (W)	V_{out} (V)	I_{out} (mA)
9 KHz	5.8998	7.21	5.396	7.42	70.85	3.96	896.08
50 KHz	5.7787	6.31	8.777	7.59	63.92	7.77	777.1
100 KHz	5.6613	5.32	7.781	7.23	53.6	5.77	677.12
500 KHz	5.7577	4.35	5.402	7.149	36.31	4.36	436.44
1 MHz	5.2047	4.253	5.343	7.131	36.61	4.514	451.43
3 MHz	0.828	3.5795	5.597	6.439	33.28	4.635	463.91
6 MHz	0.396	1.9621	5.2396	3.773	19.04	4.367	436.67
9 MHz	0.255	1.4557	5.1303	2.414	12.06	4.278	427.79
12 MHz	0.213	1.3453	5.1532	1.8767	9.39	4.254	425.42
15 MHz	0.212	1.4053	5.167	1.72	8.66	4.2598	425.98
18 MHz	0.236	1.5773	5.1353	1.7244	8.73	4.2781	427.81
21 MHz	0.278	1.9144	5.2173	1.8777	9.54	4.3084	430.84
24 MHz	0.347	2.3875	5.2582	2.1244	10.88	4.3598	435.98
27 MHz	0.452	3.0855	5.3281	2.5699	13.21	4.4205	442.05
30 MHz	0.521	3.4524	5.3352	2.966	15.1	4.4272	442.72

Table 4. Boost Converter With snubber

f_{switch}	V_L (V)	I_L (A)	V_{DS} (V)	I_{DS} (A)	$V_{DS}I_{DS}$ (W)	V_{out} (V)	I_{out} (mA)
9 KHz	5.05	7.25	5.996	7.21	68.52	3.961	896.1
50 KHz	5.153	6.215	8.83	7.17	61.26	7.826	782.6
100 KHz	5.123	5.248	7.853	7.166	54	5.841	684.07
500 KHz	4.811	4.202	5.445	7.148	36.54	4.41	441.01
1 MHz	4.755	4.463	5.5986	7.155	37.25	4.583	458.31
3 MHz	0.803	3.562	5.5891	6.527	35.2	4.651	463.12
6 MHz	0.375	1.947	5.2715	3.719	18.77	4.349	434.35
9 MHz	0.243	1.449	5.1808	2.398	12.25	4.269	426.37
12 MHz	0.199	1.337	5.1541	1.375	9.37	5.154	515.41
15 MHz	0.201	1.404	5.1541	1.744	8.75	4.247	424.73
18 MHz	0.221	1.578	5.1665	1.763	8.31	4.26	426.04
21 MHz	0.25	1.921	5.1945	1.399	9.54	4.288	428.77
24 MHz	0.323	2.403	5.236	2.1396	10.35	4.327	432.75
27 MHz	0.413	3.122	5.313	2.5888	13.04	4.406	404.56
30 MHz	0.479	3.804	5.386	3.0498	15.16	4.479	447.38

Table 5. Cuck Converter without Snubber

Frequency	Volts (Vds)	Id(amps)	VL Volts)	IL (Amps)	Vout (Volts)	Iout (Amps)	Power
9 kHz	75.673	6.97	24.16	2.218	45.928	1.837	527.441
50 kHz	75.995	6.915	24.181	2.16	44.427	1.777	525.505
100 kHz	77.005	8.678	24.21	2.14	43.984	1.759	668.249
500 kHz	75.92	10.658	24.172	2.127	40.923	1.637	809.155
1 MHz	73.55	12.318	24.148	2.118	34.616	1.385	905.989
3 MHz	71.665	6.941	24.035	2.231	19.312	0.777491	497.426
6 MHz	69.577	4.876	23.92	2.528	12.717	0.508661	339.257
9 MHz	67.542	3.984	23.971	2.909	12.079	0.483146	269.087
12 MHz	64.503	3.863	23.895	3.179	11.464	0.458565	249.175
15 MHz	60.841	3.712	23.81	3.415	10.805	0.432196	225.842
18 MHz	56.966	3.871	23.881	3.621	10.254	0.410154	220.515
21 MHz	55.062	3.881	23.743	3.747	9.669	0.396744	213.696
24 MHz	57.353	4.065	23.712	3.865	9.123	0.364934	233.141
27 MHz	57.089	3.959	23.066	3.533	7.5	0.300006	226.015
30 MHz	50.346	3.342	20.743	2.977	5.791	0.231636	168.256

Table 6. Cuk Converter With Snubber

Frequency	V_{ds} (Volts)	I_d (Amps)	V_L Volts	I_L (Amps)	V_{out} (Volts)	I_{out} (Amps	power
9 kHz	76.137	3.547	24.029	2.18	44.69	1.788	270.058
50 kHz	75.034	3.398	24.024	2.089	43.387	1.735	254.965
100 kHz	73.599	3.317	23.996	2.087	41.473	1.658	244.128
500 kHz	62.81	2.859	23.882	1.973	32.502	1.3	179.573
1 MHz	51.678	2.732	23.79	1.839	21.8	0.872003	141.184
3 MHz	37.463	2.165	17.299	1.334	7.214	0.288564	81.107
6 MHz	27.874	1.386	6.107	0.521532	1.79	0.071599	38.634
9 MHz	25.627	0.706382	2.954	0.258241	0.770839	0.030834	18.102
12 MHz	24.921	0.142148	1.676	0.153545	0.402272	0.016091	3.452
15 MHz	24.561	0.265652	0.91596	0.093557	0.216513	0.008661	6.532
18 MHz	24.38	0.17796	0.5634	0.063475	0.12258	0.004903	4.315
21 MHz	24.28	0.12378	0.32908	0.044697	0.078454	0.003138	2.986
24 MHz	24.219	0.090195	0.20743	0.0328	0.057646	0.002306	2.184
27 MHz	24.198	0.069167	0.17604	0.024993	0.05107	0.002043	1.552
30 MHz	24.196	0.054809	0.16739	0.018766	0.045787	0.001832	1.326

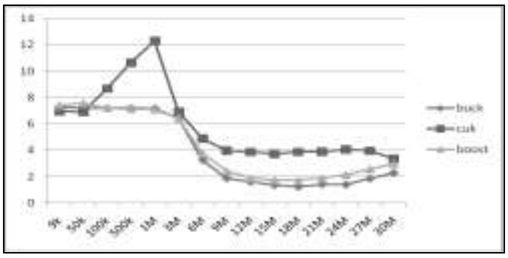

Figure 13: I_d without snubber

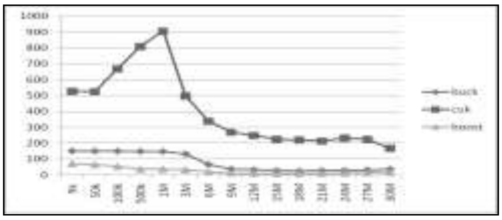

Figure 14: P_d without snubber

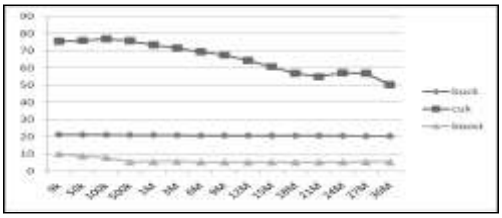

Figure 15: V_d without snubber

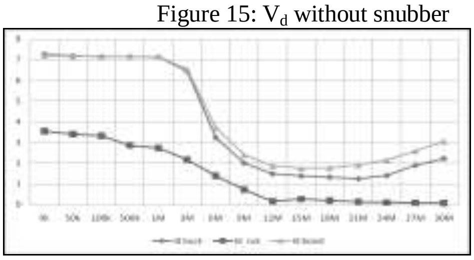

Figure 16: I_d with snubber

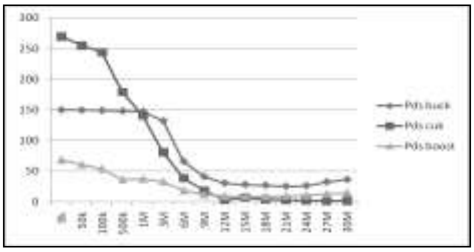

Figure 17: P_d with snubber

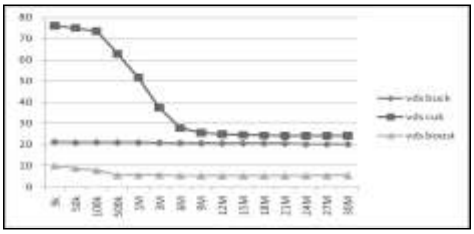

Figure 18: V_d with snubber

5. Analysis

From Figure 13, the drain current of buck, boost and Cuk converter is almost maintained for lower frequency ranges from 9 kHz to 1MHz. In the range of 3 MHz to 30 MHz there is a drastic reduction in the values of drain current. The *di/dt* effect of Cuk converter is of high value in the frequency range of 500 kHz to 3 MHz The operation of Cuk converter is not suitable for the switching frequency ranges from 500 kHz to 3 MHz, due to the high value of *di/dt* and power loss. The sudden rise in the current level will generate EMI.

From Figure 16, the effect of snubber is visualized by the significant reduction of drain current in the range of 500 kHz to 3 MHz and overall reduction of drain current for all the frequency ranges.
From Figure 15, it is identified that the voltage drop across the switch (V_{ds}) is very high when compared to buck and boost converter. It is also found that the V_{ds} is almost constant for the increasing switching frequencies of buck and boost converter.

From figure 18, it is found that by using RCD snubber the voltage drop across the switch is reduced for the switching frequencies ranges from 6 MHz to 30 MHz

It is evident from Figure 13 and 15 the Cuk converter is not suitable for low frequency ranges, unless otherwise the implementation of proper snubber circuit.
Comparing the Figure 14 and 17 it is proved that the power loss is reduced by connecting a snubber circuit and it is also inferred that the Cuk converter is much suitable for the switching frequency ranges from 6 MHz to 30 MHz.

6. CONCLUSION

This paper aimed to simulate and compare the three topologies namely the buck, Cuk, Boost and also compare the effect of a RCD snubber on each of these topologies. The converters were analyzed for different switching frequencies ranging from 9 KHz - 30MHz.It was also observed from the analysis that EMI is produced due to high switching frequency of the MOSFET. In order to reduce the EMI and increase the efficiency the RCD snubber is used and the following was found:

1. It was analyzed that the snubber was very much useful in reducing both the current and voltage spikes efficiently in the buck and Cuk converters.
2. It was found that the power loss of the converter with the snubber was smaller than that without the snubber circuit.
3. It was analyzed that the RCD snubber was not that effective in the mitigation of spikes of V_d, I_d and power loss in the case of boost converter.

7. REFERENCES

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