EMI Design for DC-DC Converters

Sandeep Tammana, Siva Yellampalli

Abstract*: *Electromagnetic interference (EMI) degrades the performance of electrical circuits and even leads to their malfunctioning. Suppressing EMI at product level is a challenge due to high frequency components in the product. Best way to suppress the effect of EMI is to optimize the circuit right at the component selection, schematic and PCB design levels. By following the best practices in the design, emissions (conducted and radiated) from the product can be reduced drastically. This paper reviews DC-DC (Buck) converters operation with respect to EMI (conducted and radiated emissions) and investigates the existing Circuit Design and PCB layout design techniques to reduce EMI in the buck converter design with the advantages and disadvantages of each technique.

Index Terms*: *DC – DC converters, EMI, EMC; RFI, PCB Synchronous buck converter, SMPS, RC snubber, RL snubber

I. INTRODUCTION

In numerous designs, electromagnetic compliance is done after the prototype stage when the design is completed. Fixing the EMI problem which is detected at this stage is costly and involves extensive filtering and shielding [1]. A design can be quite cost effective, if EMI issues are considered at a very preliminary stage. Considering the EMC during the initial phase of the design ensures a smooth and optimal product design. Component selection, proper design techniques for EMI reduction and Component placement are essential for better EMI performance of the product.

A Buck converter is a step-down DC-DC converter. Its output voltage is less than or equal to input voltage as the input voltage is chopped with switch on and off repeatedly with frequency which is termed as switching frequency. The switching frequency of a buck converter ranges from hundred kHz to a few MHz that makes it an energy efficient power converter [1]. Higher switching frequency in DC-DC converters causes Harmonics which makes Buck converters a major EMI source in most of the electronic circuits [2].

II. MAJOR SOURCES OF ELECTRO-MAGNETIC INTERFERENCE IN CIRCUITS

A. Electro Magnetic Interference

Electromagnetic interference (EMI) is a disturbance generated by an external source which could affect electrical circuit by electromagnetic induction, electrostatic coupling or conduction. This EMI disturbance might degrade the performance of the circuit if it is susceptible and even affects the functionality of the product by stopping it from functioning as intended. In case of a data path, these effects could range from an increase in error rate to a total loss of the data [3]. Both natural and man-made sources cause the changing electrical currents and voltages that leads to EMI.

Examples: Ignition blocks in automotive engine electronic control units (ECUs), Mobiles and thunderstorms etc. EMI frequently affects the FM radios, AM radios and televisions [3].

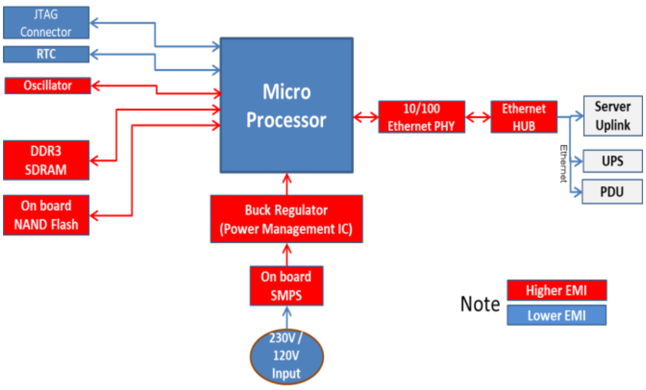

Fig. 1.EMI sources in a typical Microprocessor circuit *(Block level representation)*

All the circuits working at high frequency in a PCB are sources of EMI. Traces carrying high frequency signals will act as antennas and they tend to radiate noise Clock sources like Oscillators, High frequency clock lines, High frequency communication lines (DDR3, Gigabit Ethernet) and Switching frequencies of buck regulators are the major sources of EMI in a typical Microprocessor circuit as shown in Fig. 1.

From the above details, it is evident that DC-DC converters play a vital role as an EMI **source** in a product. Power supply is an essential circuit in any design. Conducted and Radiated emissions are high in some power supply topologies (Eg: Buck regulators etc). Following sections details about suppressing the emissions (conducted and radiated emissions) due to buck regulators and to keep the product emissions below the limits specified in the respective EMI EMC standards. Electromagnetic compatibility (EMC) is ability of a device to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances [4]. Electro Magnetic Interference (EMI) is about the emission of noise from the product. Electro Magnetic Compatibility (EMC) is about the immunity of the product to functionally work under the Electro Magnetic Environment.

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Product design targets to have less EMI and better EMC. The goal of EMC is to operate product properly in an electromagnetic environment

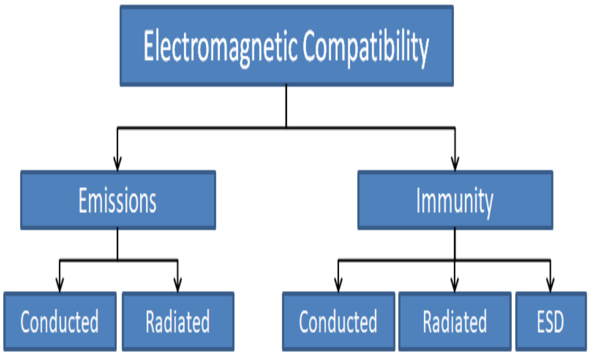

Fig. 2.EMC classification (Classification)

Permissible levels of Conducted and Radiated Emissions are regulated by numerous governing bodies. Conducted and Radiated emission levels and setup details are specified in following standards for respective products CISPR 25 for automotive products. CISPR 22 / EN 55022 standards for Information technology and multimedia equipment's. CISPR 11 is for medical equipment's. CISPR stands for International Special Committee on Radio Interference

B. Noise Coupling Types

In EMC, there is a lot of difference between radiated emissions and conducted emissions [1]. Radiated emissions are measured using various types of antennas whereas conducted emissions are measured on the supply / signal lines of a product through an LISN ("Line impedance stabilization network") and it is a part of the measurement equipment [1] Conductive, Inductive, Capacitive and Radioactive coupling from a Noise source to Victim is shown in Fig. 3.

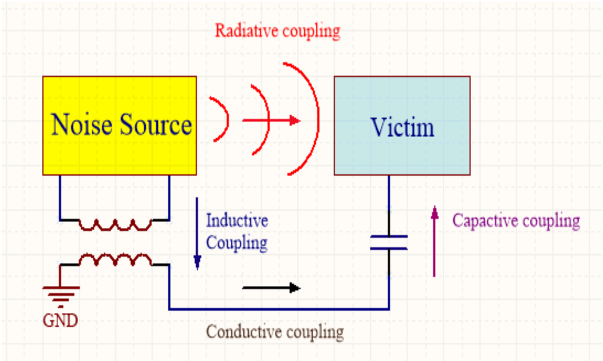

Fig. 3.Coupling (Conductive and Radiated)

EMI Sources through Conductive, Inductive, Capacitive and Radiative coupling from an Emitter to Receiver and Ways to protect Receiver from Emitter is shown in Fig. 4

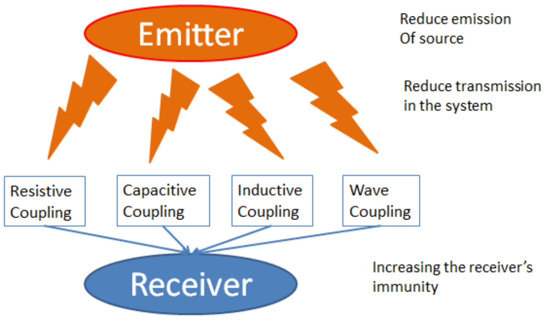

Fig. 4.EMI Sources (Common sources of EMI)

III. WORKING OF DC-DC BUCK CONVERTER

A. Buck Converter

A buck converter is a DC to DC converter which steps down voltage with stepping up current from its input supply to its output load. In synchronous buck converter, diode is replaced with a MOSFET or transistor. Additionally, buck converter contains storage elements like capacitor or an inductor or both. For reducing voltage ripple, capacitive and inductive filters are commonly added at the converter's output and at the input as shown in the Fig. 5 [6]

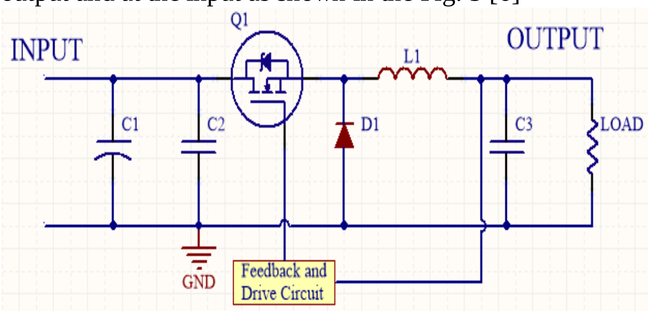

Fig. 5.Buck Converter (Detailed Circuit)

On-time of the switching element:

As the input voltage is higher than the output voltage, the current through the inductor rises and then it acquires stored energy that is supplied to output when switch opens and the current freewheels through the diode.

IV. EMI SOURCES IN BUCK CONVERTER

Electromagnetic standards and regulations provide limits to "Radiated emissions" and "Conducted emissions" that are generated when the power supply is connected to the mains. Reduced switching times in power supplies leads to faster rise and fall times for voltage and current signals. These fast edges produce more energy at high frequencies due to harmonics. These higher frequency harmonics are the root cause of most of the EMI problems in DC-DC converters. Subsequently high frequency energy causes ringing in all the resonant circuits which might stop the power supply from working as intented by complying with EMI/EMC standards[5].

A. Identifying current loops in a Buck Converter

Very high AC currents flow in two main loops in the DC/DC buck converter as shown in the Fig. 6. At ON time of high-side MOSFET Q1, current I1 flows from positive supply through MOSFET Q1, Inductor L1, output capacitor Cout and to the load. The AC current flows through the input and output capacitors. This current path is highlighted in red as I1 in Fig 6. Inductor always opposes the sudden change in current. So, when MOSFET Q1 switches off, the inductor L1 current flows in the same direction by then MOSFET Q2 is switched on and the current flows via MOSFET Q2, Inductor L1, R load and output capacitor Cout. This current loop I2 is highlighted in blue in Fig. 6. Both I1 and I2 currents are discontinuous having sharp rising and falling edges at the start and the end of active time. These sharp edges lead to high dI/dt (fast rise and fall times) producing high frequency harmonics.

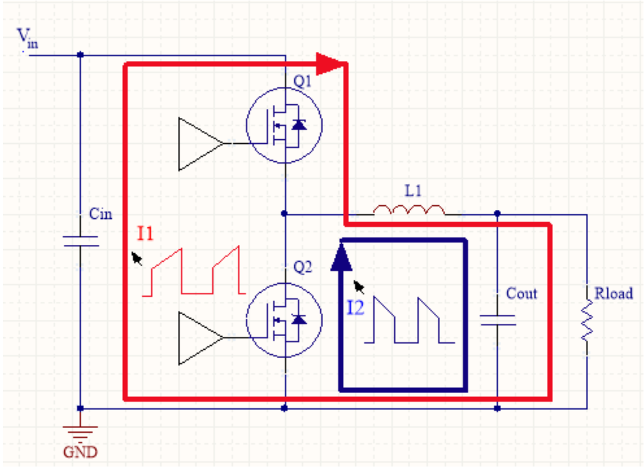

Fig. 6.BUCK CONVERTER CURRENT LOOPS (Input and Output)

Current loops shown as I1 and I2 have a common path from SW (switch) node to inductor L1, output capacitor Cout and to the source of MOSFET Q2. Sum of currents I1 and I2 results in a smooth continuous saw-tooth waveform that has smaller high frequency content (high dI/dt edges are absent). In Fig 7, shaded area A1 is the current loop with high dI/dt current. Most of the high frequencies will be generated in this loop and needs to be considered as critical loops for EMI [2].

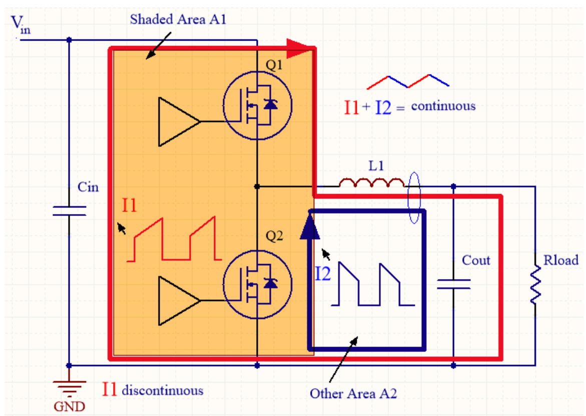

Fig. 7.BUCK CONVERTER CURRENT LOOPS (With I1 and I2) [9]

B. Input and Output Filtering

For DC – DC buck converter switching currents, a very low impedance input and output capacitors should be used. But in practical, due to Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL) of capacitors, the impedance is increased that results in the high frequency voltage drop across it. This voltage drop induces currents in the input supply line as shown in Fig. 8.

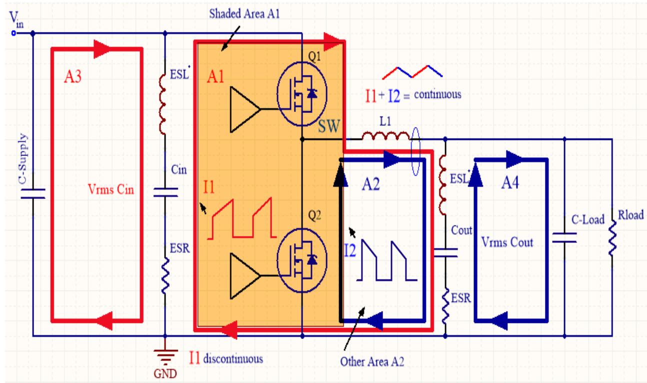

Fig. 8.BUCK CONVERTER Filtering (Input and output Filtering)

Input loop A3 could radiate more due to the longer supply lines of the buck converters and the intermittent nature of buck converter input current. This results in higher radiations and exceeding the emission levels for conducted emissions test from (150kHz ~ 30MHz band) [2].

V. EMI MITIGATION TECHNIQUES IN BUCK CONVERTER CIRCUIT DESIGN

Based on the product life cycle stage, to address the EMC of a product or to discover an EMI problem, the designer might have freedom to affect the design and apparently a better or worse chance of effectively preventing or solving an EMI problem. "Completely suppressing the noise source", "limiting the noise close to the source" are generally the preferred options. In case if the noise has coupled into different parts of a system due to various factors, controlling / limiting the emissions will be tedious.

A. Rise & Fall Time Control / Reducing the Buck Converter switching speed

In general, square wave is a combination of lots of sine waves with different frequencies superimposed together. With the switch-on speed of the high-side MOSFET Q1, the switching waveform rise time is determined. MOSFET Q1 is driven by a bootstrap capacitor C-boot. It is charged by an internal regulator in integrated buck regulator ICs as shown in Fig 9. Reducing the rise and fall times of high side MOSFET Q1 is achieved by adding a resistor Rboot in series with C-boot as shown in Fig 9 [1] [2].

Drawback: By increasing rise and fall times, the power switch operates mostly in its active region which leads to increased losses in a buck converter. In power electronics, it is always the trade-off between the EMC performance and efficiency

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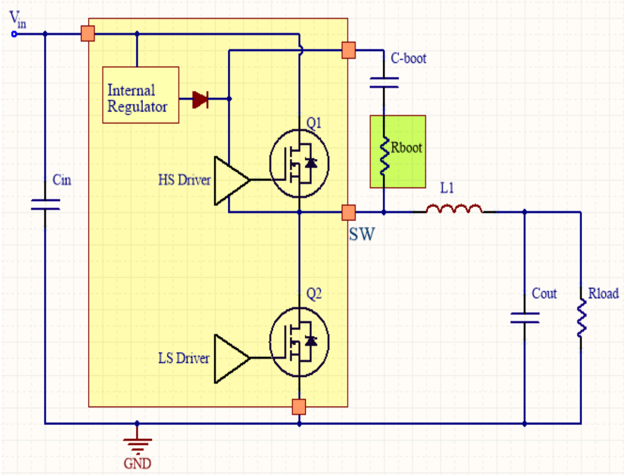

Fig. 9.Reducing switching speed with the addition of series resistor (Bootstrap circuit)

B. Spectrum Spreading

Like the rise and fall time control explained in the previous section, spread spectrum is a source suppression technique. A noise spectrum with several narrow harmonic peaks is exhibited by a converter operated with a fixed frequency and duty cycle. The frequency content could be smoothed out or spread over a larger frequency range by modulating the switching waveform in one way or another. Note that the total energy of the signal remains same and at the same time the spectral peak content is decreased [1].

C. Filtering

Buck converter is inherently noisy due to its switching action. Due to this, filtering of both input and output are therefore an essential requirement to restrict noise from spreading throughout the system. As the output of Buck converter should be a pure DC voltage, any residue from the switching must be suppressed. Input filtering is also essential as the input current of a buck converter is discontinuous. An important point to note is that common mode currents and differential mode currents generally require different filter strategies [1].

D. RC Snubber damping

In any practical converter, the square wave at the switch node in a buck converter will exhibit ringing. A Snubber network is used to limit these switching transients. There are various Snubber circuits where different combinations of the circuit elements Resistor, Inductor and Capacitor are employed. Resistive Snubber circuits will dissipate power, while Snubber without resistors can be non-dissipative. A Snubber implementation that is seen in buck converter Fig 10 is a series combination of R and C placed in parallel across the catch diode or freewheeling diode. In layout, this Snubber circuit should be placed as close as to the active switching device (MOSFET) as possible rather than to the diode. So, overall efficiency of the buck converter is compromised by the Snubber. With the suppression of overshoots and undershoots, EMI is lowered and the voltage stress on the active switching device is reduced [1].

Placing RC Snubber close to switch node and power ground is a layout best practice. RC Snubber must be placed across the drain and source of low side MOSFET in buck converters having external MOSFETs. Fig. 10 shows the placement of the RC Snubber.

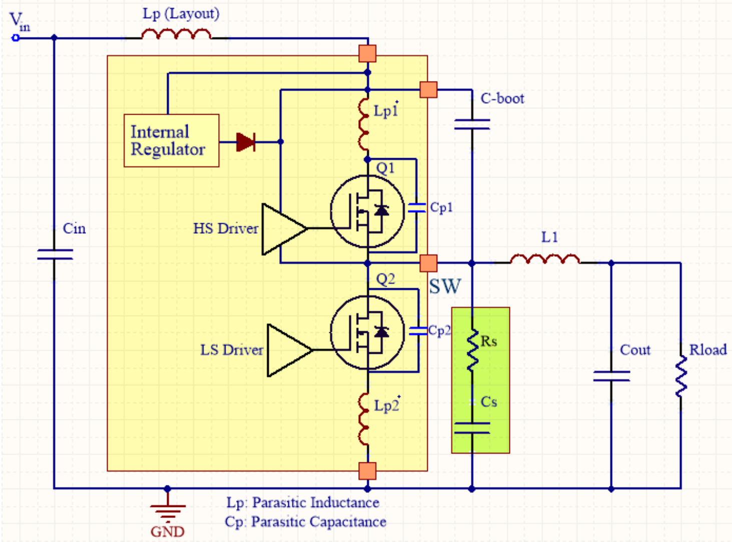

Fig. 10. RC Snubber in Buck converter (Placement)

E. RL Snubber damping

RL Snubber damping is another effective technique to reduce ringing in a switching circuit. Here RL Snubber will be added in series with the resonant circuit.

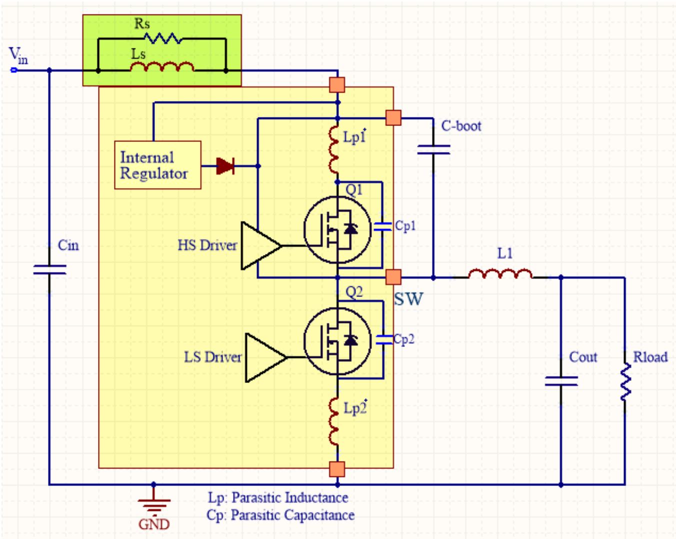

Fig. 11. RL Snubber in Buck converter (Placement)

RL Snubber provides substantial damping on the phase voltage ringing and decreases switching loop resonance at a higher rate.

Drawback: Impedance Rs is created by the RL snubber in the switching loop in high frequency region. This switch high current pulse creates a small voltage glitch across Rs during the fast switch transitions that in turn results to a small voltage glitch at input node. Buck regulator IC operation may be affected if this VIN voltage glitch is very high or low. When an RL Snubber is added, this voltage glitch on input must be analyzed and tested during maximum load switching [2].

F. Shielding

Shielding blocks electromagnetic fields and relies on different properties.

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A signal can be protected against magnetic interferences using a shielded cable with components shielded from magnetic fields by high permeability materials, which divert magnetic fields rather than block them. A shielded enclosure is a technique that effectively protects the circuit from EMI, but it is often expensive and even unpractical sometimes. So, it is not the first choice when solving an EMI problem. The switch node of a buck regulator is a source for capacitive coupling. Faraday screen is used to minimize this coupling. This is mainly applicable if the switch node is made larger. (Eg: using a heat sink [1])

Drawback: This usually is the final option for fixing the EMI issues since adding shield to circuit is quite expensive and takes additional space in the product.

VI. BUCK CONVERTER COMPONENT SELECTION

A. Inductor Selection

Selection of the inductor is an important aspect based on the core type, size, DCR (DC Resistance) and the Saturation current. The switching frequency of typical DC-DC buck regulator ICs available in the market ranges from 100 kHz to 2 MHz

Inductor Value

With high inductance ripple current will be quite small and vice versa. Ripple current is significant to determine core losses. Inductance value is an important parameter for minimizing the power loss of power inductor. The value of the inductor depends of the specification of the buck converter design.

Inductor Current Rating

Refer to the specifications mentioned in the data sheet. The nominal current of power inductors is related to self-heating with DC current. At saturation current inductance value falls by 10 %. But this is not a standard value of an inductor data sheet specification which often leads misunderstanding in few cases.

DC Resistance

It’s a best practice to choose a power inductor with possibly lower DC resistance as per the design calculations. It’s always a trade off with cost of the design too as the lower DC resistance inductors are costly.

Inductor Type

For EMC-critical applications, Magnetic shielded power inductors are recommended. Shielded inductors prevents magnetic coupling of its windings with surrounding layout (adjacent components and traces).

Buck Converter package selection

Choose smaller buck converters with low inductance flip-chip packages in noise sensitive applications. Selected package should have less input current loop as shown in Fig 12

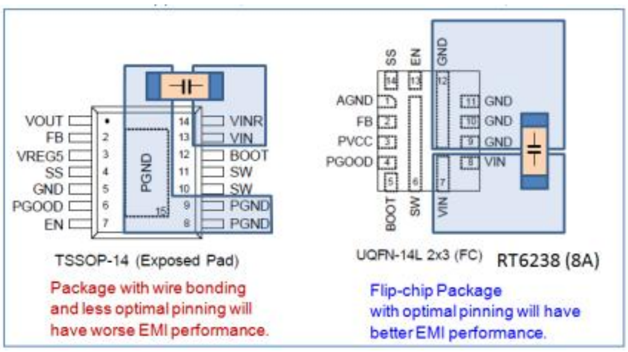

Fig. 12. Packages with different input loop area and stray inductance [2] (Package types)

VII. EMI MITIGATION TECHNIQUES IN BUCK CONVERTER

A. Reduced Switching loop

Supply and ground of the switching loop must be identified. Input switching loop should be small as shown in Fig. 13 which is best practice to reduce coupling. Input capacitors needs to be placed possibly closer to these nodes. Place the smallest size capacitor closest to the node followed by the bigger capacitors next to it. Input switching loop should be kept as small as possible as it carries very high di/dt currents.

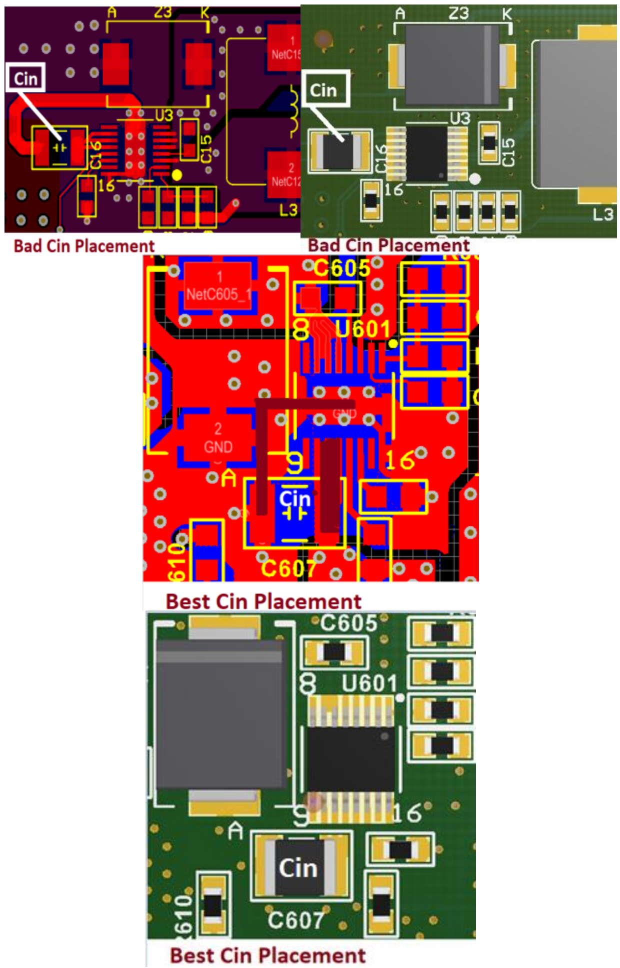

Fig. 13. Input capacitor placement (Layout examples)

B. Component Placement

Input and Output Capacitor placement

Place the output capacitor ground isolated with the input capacitor switching loop. Else this generates high frequency noise in output voltage. It also depends of type of design involved.

Placement of High power switching sections and Digital sections

The buck converter’s digital section must be isolated from the high-power switching section as shown in Fig 14.

The ground of digital section should be a clean low noise ground. Digital / Control section is not recommended to ground in the area where the input currents or output ripple currents flow [2].

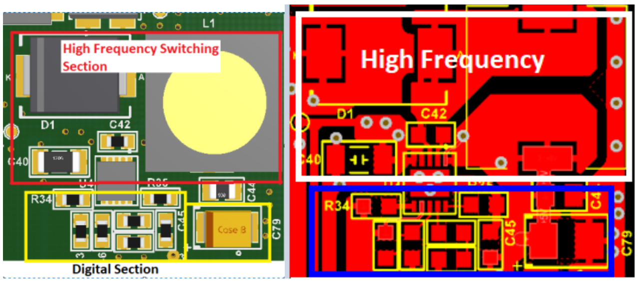

Fig. 14. High power switching and Digital sections (Placement)

C. Routing

Thermal Relief

Thermal relief in component layout should not be used for critical loops as they create extra inductance because of extra copper. But the layout design must be reviewed for Thermal design along with manufacturing feasibility.

Ground Planes

A solid ground plane must be routed below the input switching loop. It is recommended to have a solid ground without any cut in this area. Solid ground plane has more effectiveness. Signal vias also must be avoided in the ground plane as it creates holes in the ground plane that increases impedance.

Vias

Vias are for connecting one layer with another layer. Connecting a via between decoupling caps and IC ground shortens the ground loop. Via inductance increases the total loop inductance. Stitching with more vias can lower the impedance as shown in Fig 15. [2].

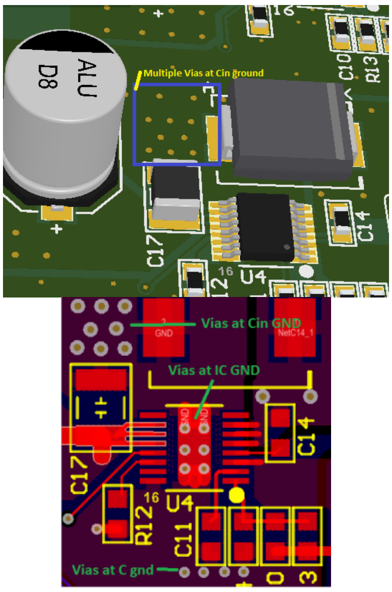

Fig. 15. Vias in the Buck regulator layout (Location)

VIII. MEASUREMENT OF EMISSIONS

Relative measurements are done to verify the emissions in the Buck converters with the implementation of the design changes specified in the above sections. Spectrum analyzer along with current probes is used for measuring the Conducted Emissions. Spectrum analyzer along with near field probes is used for measuring the Radiated Emissions.

IX. CONCLUSION

In this paper, our focus is mainly to provide major design and layout techniques that could effectively suppress the EMI in Buck converters. Initially basics of Buck converter operation and understanding on EMI/ EMC were explained. Starting with a good design on EMI, proper component selection, recommended component placement and good routing techniques can help avoiding EMI in Buck converters. The major sources of radiation in buck converters is its input switching loop on which effect of switching frequency is dominant. Reducing converter switching speed can help to reduce EMI. Shielding with ground planes can be effective provided the ground planes are solid and closer to radiating loop. Filtering of input and output supplies help to reduce conducted EMI levels. Synchronous buck converters are having lower EMI compared to buck converter type with freewheeling diode. Always it is a trade-off between the Buck converter performance and the EMC design by considering the cost factor.

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