The Basics of Conducted Emissions Testing for Switch-Mode Power Supply Designs

WHITE PAPER

Bourns® Model HCTSM8
Transformer

INTRODUCTION

Switch-Mode Power Supply (SMPS) technology has enabled a high level of efficiency of power conversion for electronic devices. By switching a MOSFET at very fast frequencies, it is possible to convert AC/DC voltages and currents to another form. However, SMPS technology has drawbacks such as the generation of switching harmonics. Converter waveforms are not a pure sinusoid and, consequently, they can generate unwanted signals that are integer multiples of the fundamental switching frequency, which are also known as harmonics. The operating topology chosen and the switching patterns deployed will directly influence the magnitude of harmonics generated. This makes pre-compliance conducted emissions testing an essential step in SMPS design.

This application note will present an informative guide to performing conducted emissions testing on an electronic device. The paper will provide the theory behind Line Impedance Stabilization Networks (LISN), conducted emissions testing apparatus and Electromagnetic Compatibility (EMC) standards - specifically CISPR 25. Additionally, a detailed explanation on how to obtain and interpret results is given. The purpose of this application note is to guide the reader through the basics of conducted emissions testing using a low-EMI (Electromagnetic Interference) DC-DC converter solution. The Bourns® Model HCTSM8 series transformers are used in dc-dc converter designs to comparatively explain how subtle differences can influence measurement results. No initial test circuits contain EMI filters to show raw noise response. For conducted emissions (CE) testing, EMI filters are implemented to drastically improve the results of the tested examples used in this paper. These findings will show that the Bourns® Model HCTSM8 push-pull transformer performs well in circuit testing, whether an EMI filter is used or not.

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THE NEED FOR EMISSIONS TESTING

To bring an electronic product to market, EMC is used to evaluate the electronic product's EMI with another product. To check EMC, the emissions that the product transmits is measured and must not exceed a certain limit. EMI emissions are defined as any unwanted electromagnetic energy from a device. This can be divided into two categories: conducted and radiated. Conducted emissions must travel via a conductor such as through wires, PCB tracks and connectors. Radiated emissions travel from the source to a receiver via air. Conducted emissions are typically coupled onto supply lines directly through conductors such as traces or wires. Radiated emissions are emitted as electromagnetic waves and can be picked up by intentional and unintentional antennas on other systems.

All electronic devices can radiate or receive unwanted electromagnetic interference, which can affect the operation of other devices/circuits. This type of radiation was considered a significant issue of concern decades ago. A good example is what can happen to television picture quality caused by other nearby devices. Military organizations became extremely concerned that these noise events potentially could trigger the firing of a missile. The solution was to implement strict EMC standards such as CISPR 25. Noise standards have enabled electronic devices to operate in closer proximity with minimal negative effects on performance.

EMI is a relatively simple problem to understand but can be a complex problem to solve. That's because EMI is a multi-sided problem with many physical and electrical factors to consider, including proper PCB layout design, the switching techniques implemented, and determination of correct EMI filter design. Moreover, transformer parasitic elements are critical to consider between primary and secondary windings. This capacitance can provide a path for common mode currents to flow across the barrier.

A push-pull topology reduces the issue significantly by incorporating a balanced switching configuration with net common mode currents cancelling each other out. The circuit used in this application note consists of the Bourns® Model HCTSM8 push-pull series transformer and the Texas Instruments Model SN6501 push-pull driver. Together, they provide a superior DC-DC converter solution with low EMI. Additionally, the Bourns® HCTSM8 transformer incorporates a toroidal core, eliminating the need for a bobbin in the finished component. Winding directly on the core also gives a higher degree of control over parasitic elements affecting specifications such as leakage inductance and capacitance between primary and secondary windings.

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UNDERSTANDING THE LINE IMPEDANCE STABILIZATION NETWORK

For conducted emissions testing, a Line Impedance Stabilization Network (LISN) must be used. There are a few reasons for its inclusion. The first is to ensure that that the source impedance is defined and matches the spectrum analyzer's input impedance. Typically, the spectrum analyzer's input impedance is 50 Ω, so the LISN's impedance will match this value. An imbalance in this situation could skew measurements. A simplistic view of the LISN is displayed in Figure 1.

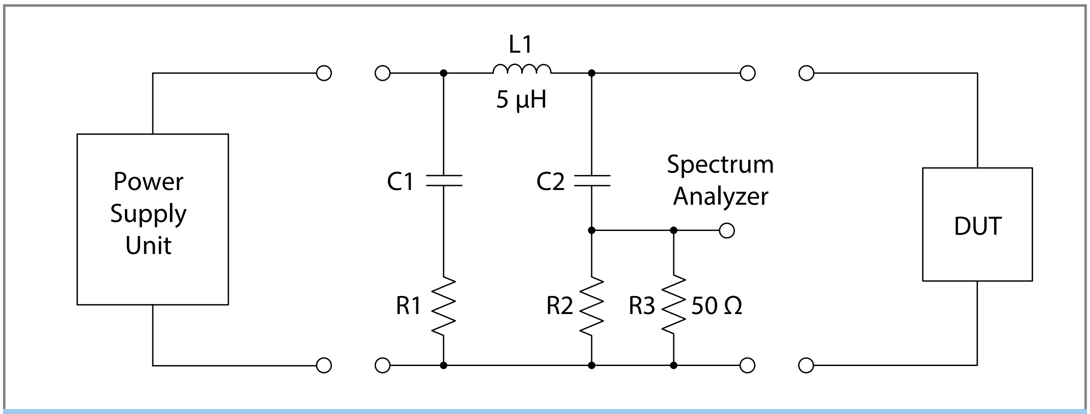

Figure 1- LISN diagram

The second reason to include an LISN is to provide an accurate noise measurement of the Device Under Test (DUT). To do this, the LISN must block any high frequency noise entering the test circuit from the power supply unit while also preventing any noise escaping through the power lines. A LISN is a two-way passive filter that operates by allowing low frequency and DC signals to flow straight through to the DUT upon power up.

Figure 1 shows that Capacitor C1 will ground most of the high frequency noise moving through as it provides a low impedance path to ground. Any remaining high frequency noise will be blocked by the 5 µH inductor. It appears as an open circuit with high impedance. In other words, the impedance becomes so high the high frequency current can't flow. Additionally, the same scenario applies to the other side where any noise generated in the circuit of interest is blocked from leaving due to the capacitor and inductor. This enables an accurate noise measurement for the DUT.

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CONDUCTED EMISSIONS TESTING

EMC is governed by standards. Manufacturers must certify standards compliance in order to release their products. Testing is the critical gate to certification. The standard stipulates the maximum amount of energy transmitted by the product during operation at different frequency bands. It defines the test set-up as well, so measurements can be benchmarked fairly. The following describes how the test is performed according to the standard.

A major consideration is that there must be a limit to the amount of emissions being transmitted from an electronic device so it does not impair the performance of any device in its vicinity. For instance, if a device is emitting large amounts of noise for a particular frequency band, this will negatively interfere with any neighboring device operating in those frequency bands. Additionally, the standard ensures that an EMC test is reproducible once the test set-up is correct.

Set-Up for the Conducted Emissions Test

The DUT is placed in an isolated room or chamber. The chamber is shielded with absorber foams on the interior of its walls. This prevents any unwanted signals from entering the room. Any other device that could emit an emission is removed from the room. The DUT is powered up through the LISN and is operated under normal conditions. The location of the LISN, DUT and antenna will all be defined in the standard. A spectrum analyzer is used to measure the emissions from the DUT across a specified frequency range and it is compared against the standards limits. A spectrum analyzer measures the noise through the LISN or through the antenna.

A special chamber was not used for the testing described in this paper. However, a lab set-up using minimal equipment can yield good results. Using an EMI testing space in a lab, the ambient noise will be much higher, and the accuracy will be lower than testing in a special chamber, but the test results still will give the engineer a good idea as to whether or not the device will pass the EMC standard. This type of lab set-up is known as pre-compliance testing. Lab testing also saves time and money by avoiding an off-site EMC test house that charges chamber rental fees. All one needs for pre-compliance EMC testing in the lab is an LISN, ground plane, spectrum analyzer and a power supply unit or a battery. Using a linear power supply is recommended as it generates much less noise than switch-mode power supplies. Figure 2 displays the test set-up used in this paper in accordance with the CISPR 25 standard.

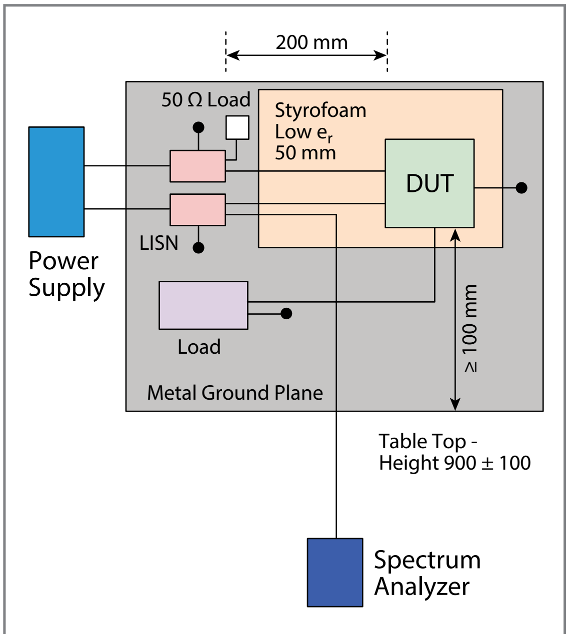

Figure 2 - CISPR 25 conducted emissions measurement set-up

CONDUCTED EMISSIONS TESTING (Continued)

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CISPR 25

There are many standards used for DC conducted emissions such as CISPR 22, as well as CISPR 11. The CISPR 22 standard is primarily used for Information Technology Equipment (ITE) such as computers, servers and keyboards, while the CISPR 11 standard deals with industrial, scientific and medical equipment. For this paper, the CISPR 25 standard is applied, and this is the automotive standard that is adhered to. It is defined as the "Radio disturbance characteristics for the protection of receivers used on-board vehicles, boats, and on devices – Limits and methods of measurement."

The test for the CISPR 25 standard measures conducted emissions in the 100 kHz – 108 MHz frequency range. There are different classes defined in the standard, and a specific device's class will be chosen based on where it is used in a vehicle system. There are five classes used where Class 5 has the most strict limits. The permissible limits are displayed in Table 1 and Table 2.

Table 1. CISPR 25 peak and quasi-peak limit levels

Service / Band	Frequency (MHz)	Levels in dBµV									
		Class 1		Class 2		Class 3		Class 4		Class 5	
		Peak	Quasi-Peak	Peak	Quasi-Peak	Peak	Quasi-Peak	Peak	Quasi-Peak	Peak	Quasi-Peak
Broadcast											
LW	0.15 - 0.30	110	97	110	87	90	77	80	67	70	57
MW	0.53 - 1.8	86	73	78	65	70	57	62	49	54	41
SW	5.9 - 6.2	77	64	71	58	65	52	59	46	53	40
FM	76 - 108	62	49	56	43	50	37	44	31	38	25
TV BAND 1	41 - 88	58		52		46		40		34	
Mobile Services											
CB	26 - 28	68	55	62	49	56	43	50	37	44	31
VHF	30 - 54	68	56	62	49	56	43	50	37	44	31
VHF	64 - 87	62	49	56	43	50	37	44	31	38	25

Table 2. CISPR 25 average limit levels

Service / Band	Frequency (MHz)	Levels in dBµV				
		Class 1	Class 2	Class 3	Class 4	Class 5
		Average	Average	Average	Average	Average
Broadcast						
LW	0.15 - 0.30	90	80	70	60	50
MW	0.53 - 1.8	66	58	50	42	34
SW	5.9 - 6.2	57	51	45	39	33
FM	76 - 108	42	36	30	24	18
TV BAND 1	41 - 88	48	42	36	30	24
Mobile Services						
CB	26 - 28	48	42	36	30	24
VHF	30 - 54	48	42	36	30	24
VHF	64 - 87	42	36	30	24	18

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CONDUCTED EMISSIONS TESTING (Continued)

Conducted Emissions Measurement

A spectrum analyzer is used to measure the level of noise for conducted emissions testing. Output is displayed in graph form. The standard defines limit lines in Quasi-Peak (QP) values, Peak values and Average (AV) values. These are all different ways the spectrum analyzer measures noise before displaying it.

Quasi-peak detection is the slowest by an order of two or three magnitudes to peak detection. It is based on weighted averaging that has a fast rise time constant but a slow fall time constant. The faster the repetition, the higher the weight applied to that component. The peak detection is the fastest of all EMI scans as it just takes the peak value of noise signals. The average detection method gives the average amplitude of each signal component across its period.

For pre-compliance, the best practice is to begin with peak detection. If the peak test is below the QP limit, then in the majority of cases, it will pass the QP and AV limits as well. If the peak test at a certain frequency is above the QP limit, then it is advised to switch to the quasi-peak limit and the average value detection at that frequency. Taking this approach speeds up the testing and debugging process.

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TESTING BOURNS® HCTSM8 TRANSFORMERS

The Bourns® HCTSM8 push-pull transformer series are used in isolated gate drivers or in battery management systems (BMS) for industrial automation, process control, low/medium risk medical equipment*, and isolated interface power supplies for CAN, RS-485, RS-422, RS-232, SPI, I²C, and low power LAN applications. They have been tested and approved by Texas Instruments (TI) for use with their SN6501 push-pull driver. The TI SN6501 requires a few extra components apart from the Bourns® HCTSM8 transformer to deliver isolated 5 V and anything up to 300 mA DC. To illustrate EMI performance, EMC testing of a push-pull circuit using the SN6501 and HCTSM8 were conducted. The tests achieved benchmark measurement results against the standard and were compared with other push-pull drivers on the market.

Figure 3 displays the test circuit used for the EMI testing and this circuit will be denoted Circuit 1. Figure 4 shows the schematic of the push-pull circuit with the HCT transformer as before, but using a different transformer driver chip. This is used for benchmarking purposes and to show the benefits of using a simple transformer driver compared to a more complicated one.

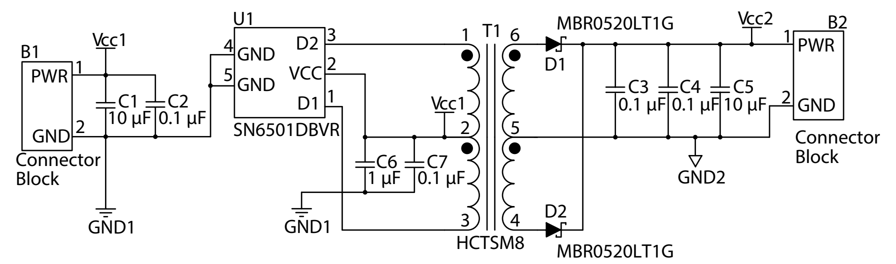

Figure 3 - Circuit 1 schematic

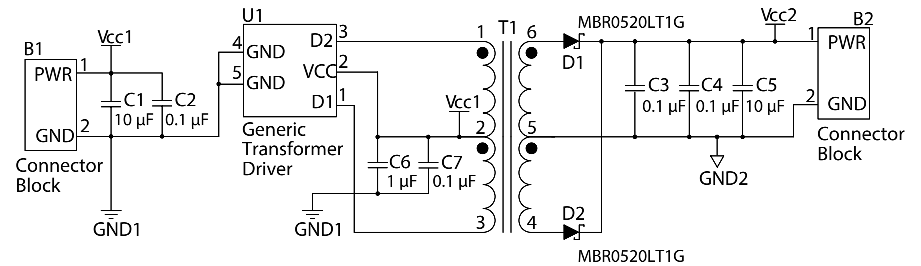

Figure 4 - Circuit 2 schematic

Performing an EMI-based comparison between two different circuits can be difficult, as EMI is a complex problem with many different factors to consider. Transformer parasitics, the PCB layout design, switching techniques and a correct EMC filter design all uniquely impact emissions. Subtle differences can result in huge changes, but comparisons performed in this paper are designed to show how some simple changes, such as using a different chip, can affect EMI performance.

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TEST SET-UP AND PROCEDURE

The set-up is displayed in Figures 5, 6 and 7 for the conducted emissions testing. The set-up is in accordance with the CISPR 25 standard. In the test, a linear power supply supplies 5 V for Circuit 1 and 24 V for Circuit 2 through the LISNs. Two LISNs are used on each power line. A 50 Ω load is terminated on the return LISN port, while the LISN on the supply line is used to supply the noise measurements to the spectrum analyzer. A 100 Ω resistive load is connected to the DUT. In the first part of the test, an ambient scan is captured prior to turning on the power. The circuit is powered up from 0-5 V and then a peak measurement is performed to capture the results. The highest harmonic amplitudes will be compared to the standard.

Four circuits were tested. The first circuit was tested three times with three different Bourns® HCTSM8 series transformers. The first circuit has a 1:1 turns ratio, the second one has an 8:9 turns ratio and the third circuit has a 3:5 turns ratio. The same load is applied to each circuit and consequently, the load current drawn will differ. This will give the tester a good view of the impact power has on the emissions.

In the last part of the test, an alternate IC chip is used in a circuit. The transformer used is a Bourns® push-pull transformer that is similar to the Bourns® Model HCTSM8. The comparison is provided to show how the complexity of circuits can influence EMI performance. Note that there are no EMI input filters used which are normally essential for reducing harmonics. This setup may annoy the experienced electronics designer as it is akin to driving blindfolded. However, the goal of the paper is to familiarize the reader with conducted emissions fundamentals.

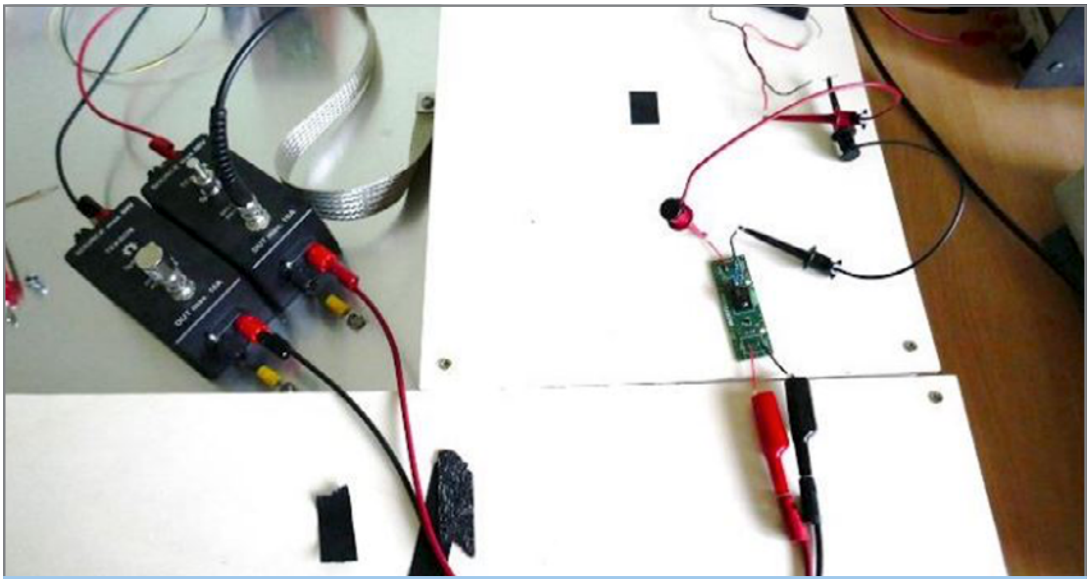

Figure 5 - Conducted emissions set-up displaying LISNs and DUT

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TEST SET-UP AND PROCEDURE (Continued)

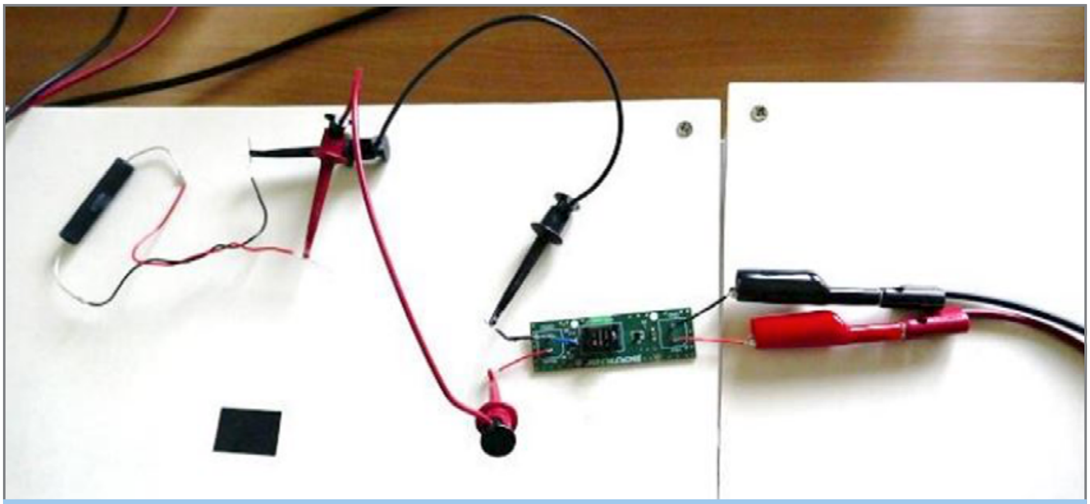

Figure 6 - Conducted emissions set-up showing DUT with 100 R load

Figure 7 - Conducted emissions set-up showing scope and spectrum analyzer

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TEST RESULTS

A peak detection and average detection scan were performed and tested. Peak detection is denoted in red while the blue trace is for average detection measurement. Note that the CISPR 25 Class 5 standard was chosen for evaluation to tightest noise limits. The green line displayed in the results indicates the quasi-peak limit level for a specific frequency band, while the blue line shows the average limit level for a specific frequency band. If a peak detection harmonic is within 6 dB of the quasi-peak limit level, it is good practice to determine it as a failure at that frequency band. For simplicity, peak detection measurement and quasi-peak limit levels will be discussed only in the results. The largest amplitudes are cross-referenced with the quasi-peak limit levels.

Ambient Trace

The ambient trace is displayed in Figure 8. This is an important step to execute prior to testing. If there are any large harmonics present, the tester will need to subtract the amplitude from any results measured. The testing chambers would have a much quieter ambient trace.

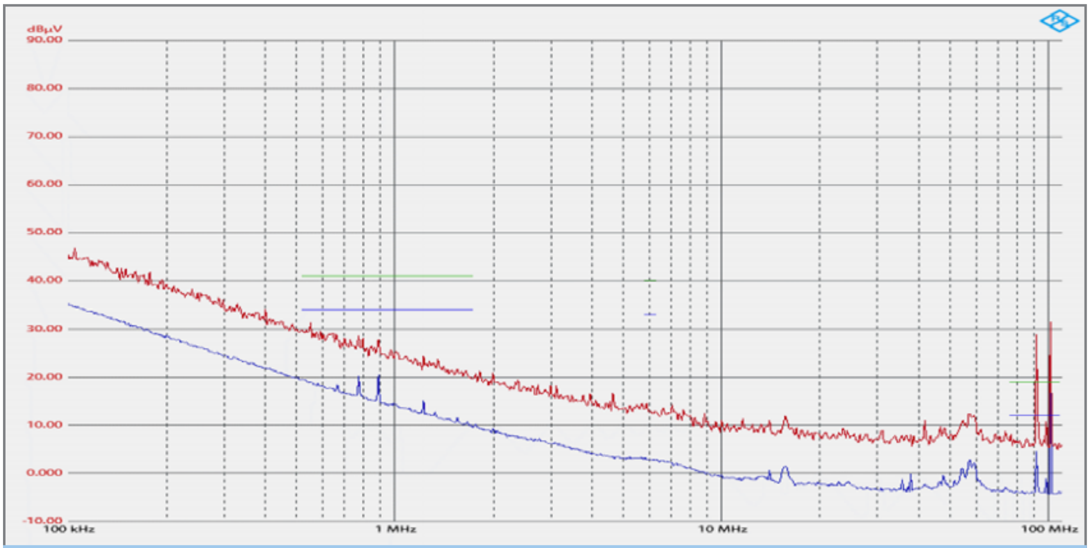

Figure 8 - Ambient trace

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TEST RESULTS (Continued)

Test Results for SN6501 and Model HCTSM80809AAL

V_{in} = 5.00 V, I_{supply} = 76 mA, Load = 100 R, V_{load} = 5.427 V

Figure 10 displays results from the Bourns® Model HCTSM80809AAL transformer. Note that results differ from the previous graph. At 3-10 MHz, the DUT marginally passes. The harmonics measured are roughly 35 dBμV while the limit is defined as 40 dBμV. At 100 MHz, there is a large harmonic amplitude of 35 dBμV. Subtracting this from the ambient trace, it passes the standard limit.

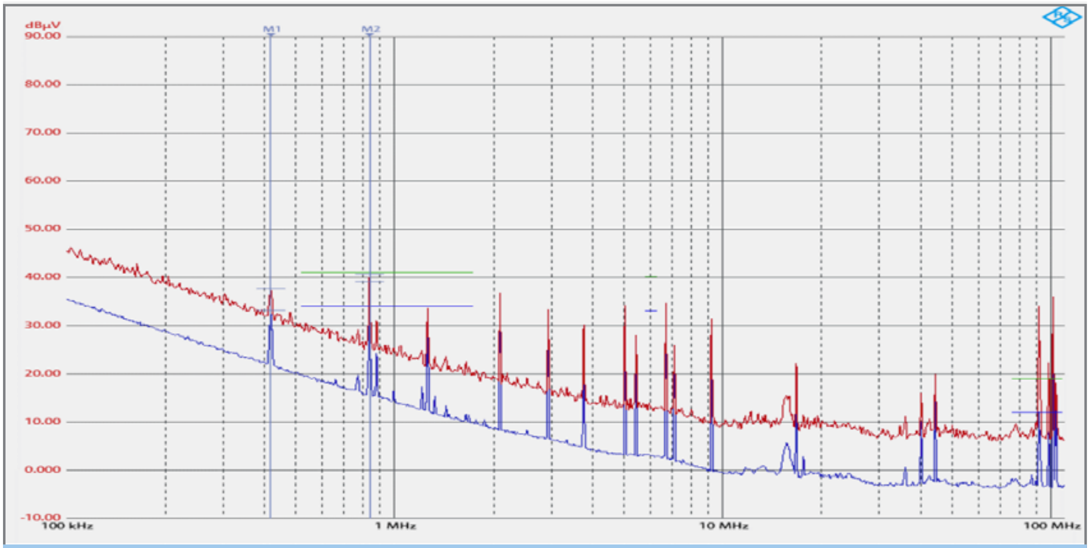

Figure 10 - Circuit 1, Model HCTSM80809AAL conducted emissions results

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TEST RESULTS (Continued)

Test Results for SN6501 and Model HCTSM80305BAL

V_{in} = 5.00 V, I_{supply} = 142 mA, Load = 100 R, V_{load} = 7.76 V

Figure 11 shows resulting conducted emissions from the Model HCTSM80305BAL transformer. This transformer draws more power, so consequently there is more noise. The harmonic amplitude at 820 kHz roughly equates to 45 dBµV and exceeds the 41 dBµV limit per the standard. In similar fashion, from 26–87 MHz there are three harmonics present that exceed the 31 dBµV and 25 dBµV standard limits.

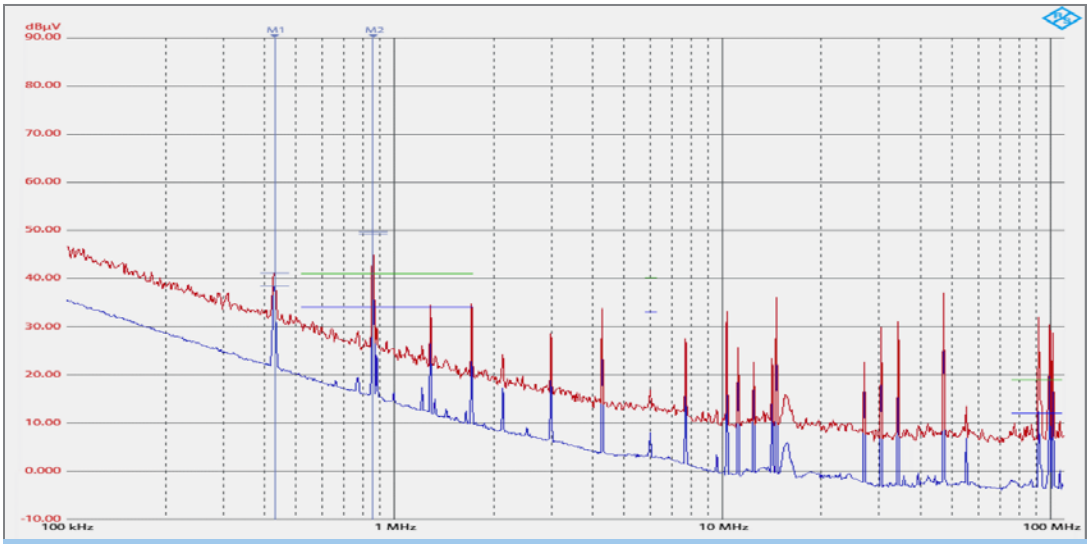

Figure 11 - Circuit 1, Model HCTSM80305BAL conducted emissions results

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TEST RESULTS (Continued)

Test Results using a Bourns® Push-Pull Transformer with an Alternative Push-Pull Driver

V_{in} = 24 V, I_{supply} = 135 mA, Load = 50 R, V_{load} = 10.29 V

An HCT series transformer was tested with an alternative push-pull driver (Circuit 2) so that EMI performance could be compared to Circuit 1 which contains the Bourns® Model HCTSM8 transformer series and the TI SN6501 driver. The fundamental switching frequency of the chip is 500 kHz and can be seen Figure 12. The second harmonic amplitude is evident at 1 MHz, and exceeds the 41 dBµV limit. Between 1 MHz and 10 MHz, all harmonics present on this graph either exceed or are close to the applicable noise limits. The different chip is more complex by nature, coinciding with the higher power rating. This explains the higher harmonic amplitudes displayed.

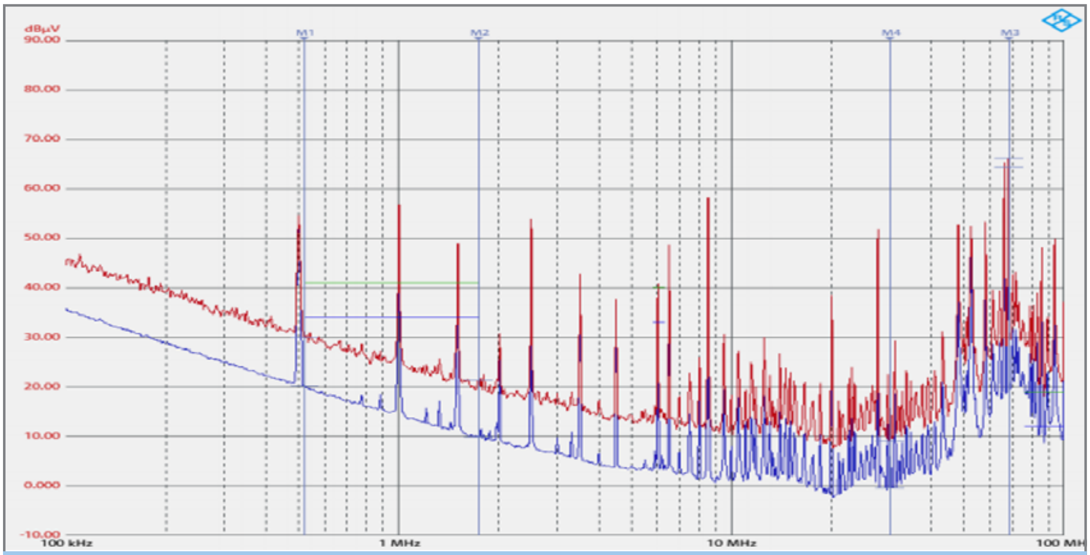

Figure 12 - Circuit 2, alternative transformer driver and Bourns® push-pull transformer conducted emissions results

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CONCLUSION

Designers of DC-DC power converters require a finished circuit that not only provides necessary power and efficiency goals at a competitive price but also one that is compliant to all applicable EMC regulations. This paper provided an overview of EMC requirements. This included details on tests performed by Bourns on both an isolated 5 V solution using a Bourns® Model HCTSM8 transformer and TI SN6501 driver IC circuit design. Alternative push-pull driver ICs were also tested to compare EMI test results with the Bourns/TI driver circuit. Measured results from testing were discussed and this data demonstrates that the combination of using the TI SN6501 and Bourns® Model HCTSM8 solution was helpful in meeting standards compliance and required fewer interventions, ultimately contributing to a shorter time to market.

Summary Findings and Results

- A circuit (Circuit 1) was constructed using a Bourns® Model HCTSM8 transformer and TI SN6501 chipset.
- Several different Bourns® Model HCT Series transformers were used with the TI SN6501 driver for measurements at various supply currents and output voltage levels.
- Another circuit (Circuit 2) was constructed using a Bourns® Model HCTSM8 transformer and an alternate push-pull chipset for comparison testing.
- All circuits were tested according to CISPR 25, Class 5 for pre-compliance conducted emissions testing.
- The DUT passes or marginally fails without any EMI filter design. This confirms that the combination of the Bourns® Model HCTSM8 transformer in the TISN6501 driver circuit provides an adequate low EMI DC-DC solution.
- Conversely, the use of an alternate push-pull driver circuit displayed much higher emissions and its harmonics exceeded the limits in nearly all frequency bands.
- The largest harmonic present in Circuit 1 was 45 dBµV, while in Circuit 2 the largest harmonic was 65 dBµV.
- Circuit 2 showed a much larger concentration of emissions in the 10 MHz to 100 MHz frequency band than results from Circuit 1.
- Because of the higher input and output power, the Circuit 2 chip contained more components that likely resulted in higher overall emissions.

REFERENCES

1. CISPR 25, Edition 3.0 2008-03, Vehicles, Boats and Internal Combustion Engines – Radio Disturbances Characteristics – Limits and Methods of Measurement for the Protection of On-Board Receivers.
2. Texas Instruments, Sep 2016, CISPR 25 Tested Automotive Tail Light Reference Design for Step-up and Linear LED Driver-Based Systems.
3. Texas Instruments, Jan 2021, SN6501 Transformer Driver for Isolated Power Supplies

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