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EMC+SIPI Talks Reveal More About EMI Filter Design For Flyback Converters

by Kevin Parmenter, Chair, and James Spangler, Co-chair, PSMA Safety and Compliance Committee

In a recent column, we presented highlights from the first week of the 2020 IEEE EMC+SIPI Virtual Symposium, which was held Aug 3-28, 2020.[1] That article was intended to familiarize readers with the breadth of topics covered at this annual conference—from the perspective of a power electronics engineer—while also giving readers a chance to take part in the program through this year's online format. While many of the presentations at EMC+SIPI addressed electromagnetic interference (EMI) and electromagnetic compliance (EMC) issues broadly, some of the talks had a power electronics focus.

This article focuses on two such presentations on EMI filter design by Michael Schutten and Cong Li of GE Research. These talks, which were titled "EMI Noise Separation and Filter Design for a Switch-Mode Power Supply"[2] and "EMC Fundamentals for Switch-Mode Power Converters,[3] offered practical information on filter design for low-power flyback converters, which continue to be a very popular topology in the industry. Not only were these talks interesting on their own, they also were similar to work that I (Jim) and my co-authors presented at the Power Electronics Technology (PET) conference in 2002, from the paper "Solving EMI for Low Wattage Universal Input Power Supplies".[4]

All of these talks explained and demonstrated how the various components used in an EMI filter affect the line-conducted noise. One difference is that the earlier work in 2002 did so for the case where a two-wire ac line cord is used, while the recent EMC+SIPI presentations focused on the use of a three-wire ac line cord. Additionally, these recent presentations showed both the common mode (CM) and differential mode (DM) noise for each section of the filter and gave the method used to separate the CM and DM noise for design purposes. In contrast, these noise components were not treated separately in the earlier work.

Despite their differences—or perhaps because of them—all three of these presentations are useful for educating engineers on which components and component placements determine how effective EMI line filters are in reducing line-conducted electromagnetic-interference noise (EMI). The methods discussed allow for a first-pass cookbook approach to designing an EMI filter for low-power flyback applications. In this article, we'll discuss and compare these presentations to highlight what power supply designers can learn from them.

Background

In the 2001-2002 time frame, I (Jim) gave switched-mode power supply seminars for On Semiconductor in the U.S., Canada and Mexico. At that time, the flyback converter topology was the main choice for designs less than 100 W. Many designs needed multiple output voltages and the flyback transformer allows for different voltages without the need of a post regulator.

This helps to explain the choice of the power supply example in the 2002 conference presentation. It was a 20-W power supply for a set-top box for cable TV or a satellite receiver for TVs. The dc output voltages were 3.3 V, 5.0 V, 12 V, and 33 or 38 V. Two different designs were given. The first was based on a 100-kHz fixed-frequency switching regulator in an isolated 5-pin TO-220 package (the NCP1001P, now an obsolete part), while the second was built around a critical conduction mode switching regulator (the MC33363), operating between 70 and 85 kHz, with an external 600-V MOSFET.

The purpose of the presentation (and paper) was to show that the EMI filter components can be applied to the designs in a "cookbook" approach to help speed up the design process. It also was used as a teaching aid for engineers to help prepare their designs for production. The takeaway for designers was that the main EMI components available to them to control line-conducted noise are X capacitors, Y capacitors, and the common-mode choke. The designs presented used a two-wire line cord with an earth or protected ground. And as noted above, the 2002 paper failed to address CM and DM EMI noise.

According to Schutten, the 2020 EMC+SIPI research presentation[2] was also a 20-W design with a single output operating at 70 kHz. In that presentation, Schutten and Li presented the effects of the various EMI filter components using the same type of components as in the 2002 paper. But in the Schutten and Li talks, they presented their common-mode and differential-mode switchable test setup to help better determine the effects of each component as it is placed in the EMI filter. For each component an EMI spectrum was presented on both the ac hot (L1) and ac neutral (return) (L2). Their work concentrated on a power supply with a three-wire ac power cord.

As with the 2002 presentation, the purpose of the EMC+SIPI presentations was to educate design engineers as to how the various EMI filter components affected the line-conducted noise. However, the Schutten and Li presentations[2,3] provided greater detail than the 2002 PET Conference presentation[4] mainly due to the greater time allowed for the EMC + SIPI sessions.

Three-Wire Vs. Two-Wire AC Power Cord

The electrical energy supplied to an offline power supply is from the power grid (or mains). This power is often supplied using a two-wire or three-wire electrical power cord in North America (NA). Most ac-powered appliances today use a universal-input switched-mode power supply able to operate from 100 Vac (Japan), 120 Vac (North America) and 230 Vac (Europe).

A two-wire power cord is often used in NA when there is no exposed metal that the consumer can touch. When there is exposed metal, a three-wire power cord is used, which includes conductors and prongs for ac hot, ac neutral, and earth ground.

It should be noted that a three-wire ac power cord is often used in many laptop computer power supplies where the dc output barrel on the connector is directly connected to the protected earth. Some medical supplies such as a power supply for a CPAP machine, which is often double isolated, use a two-wire line cord. An example product would be the Phillips' DreamStation, a CPAP machine with a two-wire cord.

EMI Filter Components

The basic EMI line filter is shown in Fig. 1 with components, including both the real and parasitic components. This schematic is common for almost all switched-mode power supplies. The intentional components are in blue while the unintentional or parasitic components are in red.

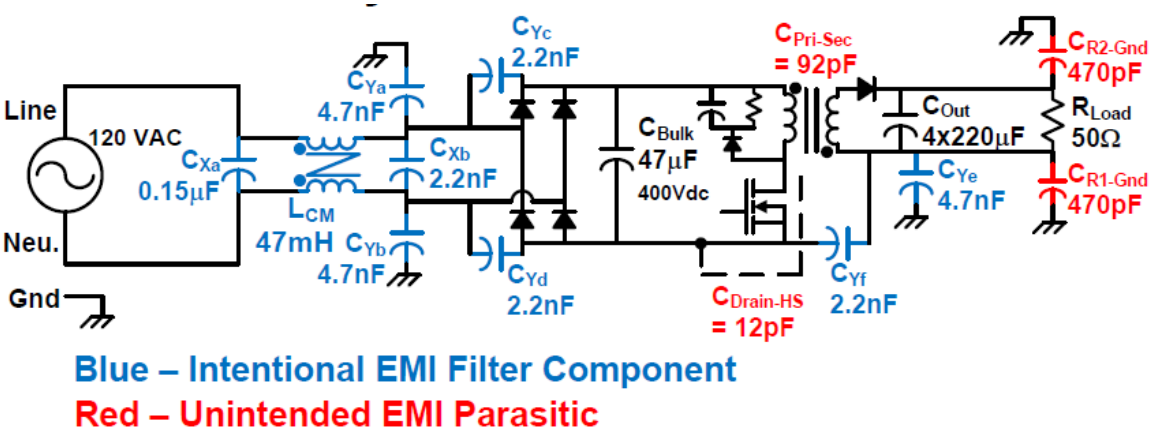


Fig. 1. Basic line-conducted EMI filter showing both intentional and unintentional (parasitic) components. (See page 2 of reference 2.)

The basic EMI line filter is composed of various X rated capacitors, Y rated capacitors, a common-mode inductor, and voltage transient suppression components like metal oxide varistors (MOVs). There is no MOV shown in these designs. The MOV would normally be placed in parallel with the C_{Xb} capacitor, see Fig. 1, to absorb electrical voltage transients. I (Jim) believe that the MOV is a necessary component, for achieving a more reliable power supply design.

When doing a filter design it is recommended that the following components be placed on a pc board with different component hole spacings. From a project planning perspective, it is also recommended that you allow for three pc-board layouts in the design budget to accommodate possible design changes to meet both physical layout changes and engineering component changes in order to pass the EMI line conducted and EMI radiated emissions tests.

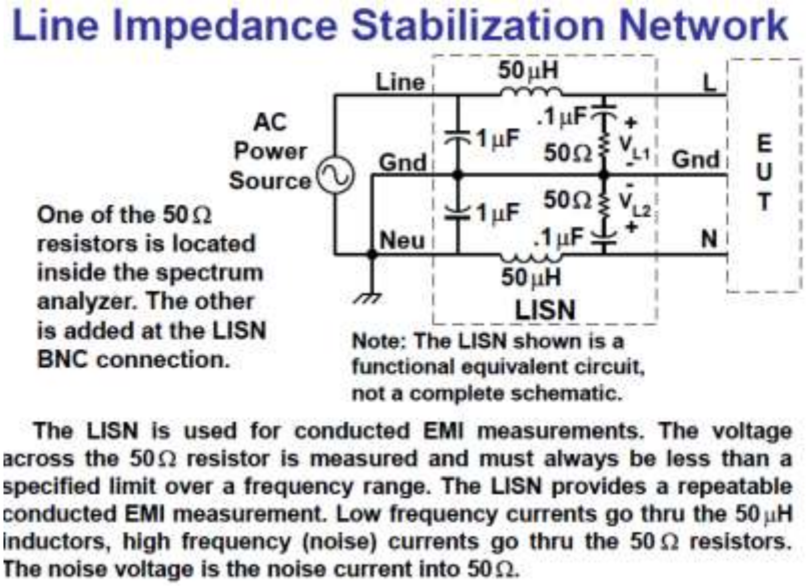
The EMC+SIPI presentation[2] tested five boards: A, B, C, D, and E showing the effect of each EMI filter component as parts were added to the board. The table below lists the filter components that were present on each test board. As the board descriptions indicate, the first board had no filter components installed, and then each subsequent board added filter components without taking away any components that were on the previous board.

The table also indicates where in the EMC+SIPI presentation you'll find the associated board schematic and where you'll find the associated EMI measurements. However, all of the components listed here are shown above in Fig. 1 and the EMI measurement results will be repeated later in this article.

Table. EMI filter test boards.

Board	Description of EMI filter configuration, specifying which components are installed	EMI Results (L1, L2, CM, DM) shown in presentation on this page	Schematic page in presentation
Board A	No EMI components installed (for baseline noise measurement)	7	6
Board B	Only the common-mode choke L_{CM}, C_{Yf} (2.2 nF) and C_{Ye} (4.7 nF)	10	8
Board C	Common-mode choke, C_{Yf} and C_{Ye}, plus Y caps C_{Ya} and C_{Yb} after CM choke	12	11
Board D	Common-mode choke, C_{Yf} and C_{Ye},, Y caps C_{Ya} and C_{Yb} after CM choke, plus Cxa	14	13
Board E	Common-mode choke, C_{Yf} and C_{Ye},, Y caps C_{Ya} and C_{Yb} after CM choke, Cxa plus C_{Yc} and C_{Yd}	16	15

Testing was performed using a dual line impedance stabilization network (LISN), as shown in Fig. 2. (This was taken from page 4 of the Schutten and Li presentation[3]). Fig. 3 was added to show that there are 50-Ω terminations across the resistors.



Line Impedance Stabilization Network

One of the 50Ω resistors is located inside the spectrum analyzer. The other is added at the LISN BNC connection.

Note: The LISN shown is a functional equivalent circuit, not a complete schematic.

The LISN is used for conducted EMI measurements. The voltage across the 50Ω resistor is measured and must always be less than a specified limit over a frequency range. The LISN provides a repeatable conducted EMI measurement. Low frequency currents go thru the 50µH inductors, high frequency (noise) currents go thru the 50Ω resistors. The noise voltage is the noise current into 50Ω.

Fig. 2. Basic dual LISN schematic for EMI noise measurement. (See page 4 of PowerPoint presentation given in reference 3.)

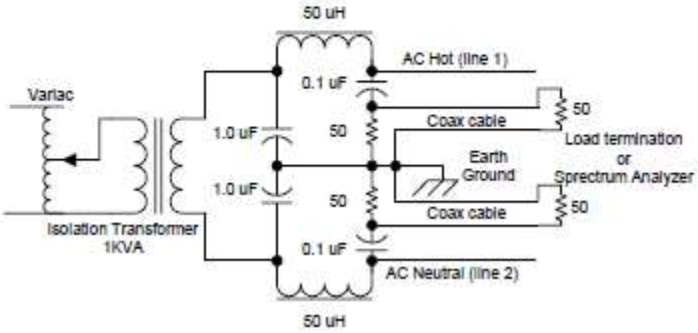


Fig. 3. A dual LISN showing 50-Ω terminations for a spectrum analyzer or network analyzer. This LISN, which was used in the 2002 presentation, was an EMCO model 3810/2 modified by changing the 0.47-μF capacitor to a 0.1-μF capacitor. This was done to meet the FCC Class B, part 15, sub-Part J limits. This figure was taken from Fig. 1 given in reference 4.

Separating The Differential Mode And Common Mode Waveforms

In their presentation,[2] Schutten and Li presented a schematic of a test box placed between the LISN and the spectrum analyzer. The schematic is shown Fig. 4. The L1 output is normally from the ac hot side of the LISN as shown in Fig. 3, while the L2 is from the neutral side of the LISN output going to a 50-Ω impedance. The output of the DM/CM separator box goes to a spectrum analyzer.

Note the four-position RF switch is a coaxial type that is on a remote control. This allows the ability to switch in the various waveforms to the spectrum analyzer to record data without disconnecting all the equipment and cables. This maintains quality of the signal.

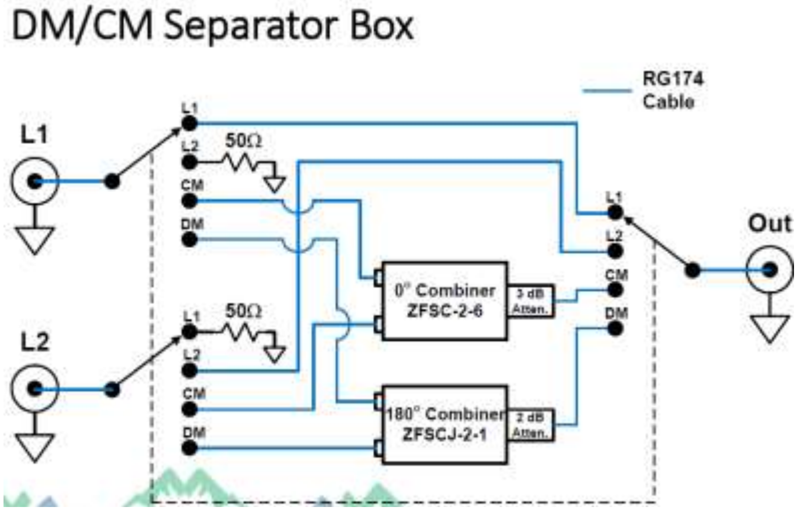


Fig. 4. Differential mode and common mode separator box with output to a spectrum analyzer. The DM/CM separator uses MiniCircuits combiners as shown here. There is an additional attenuator following each combiner to provide exact noise levels.

Results Of Tests Specified In The Table

Fig. 5 is a graph of the limit taken from the EMC+SIPI presentation.[2] This states the limits in dBμV (minus dB microvolts as compared to 1.0 Vrms).

The first series of scope shots (Fig. 6) shows the noise floor without any EMI components on the board. These are the measurements taken on Board A as described above in the table. It is hard to know the limits in the scope shot due to all the signals being in the middle.

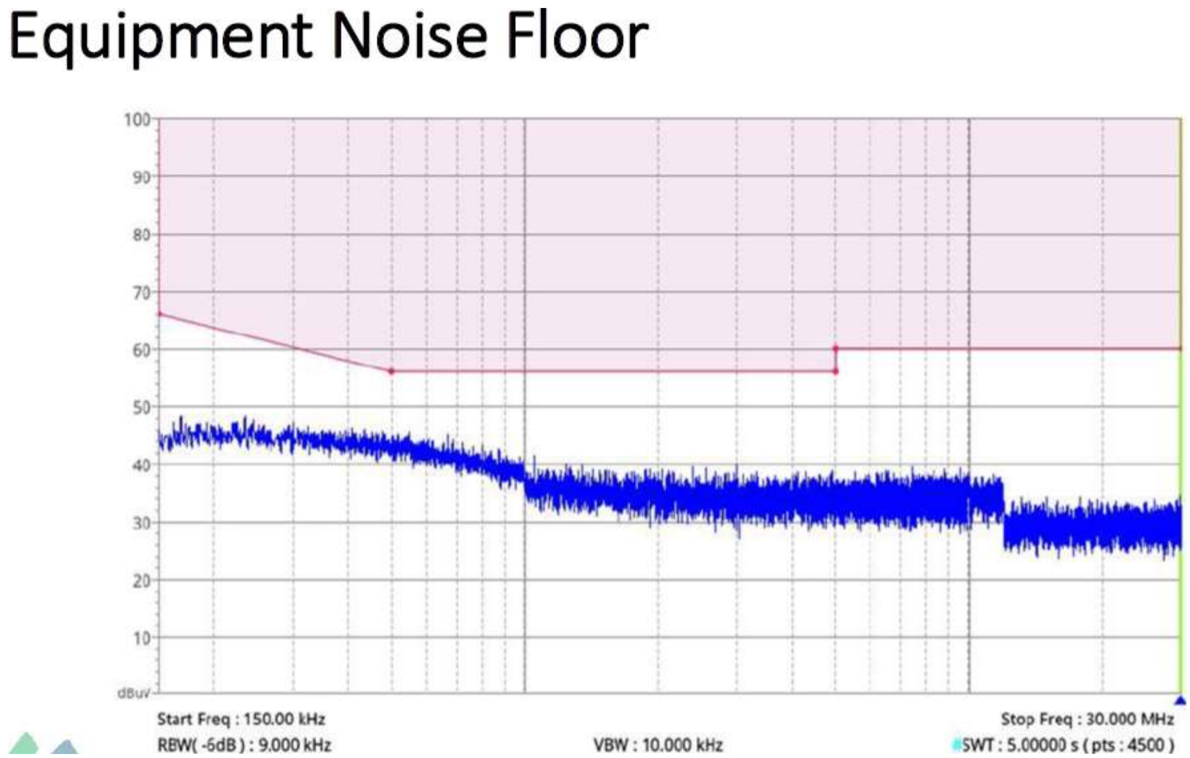

Equipment Noise Floor

Fig. 5. Equipment noise floor taken from page 4 of reference 2.

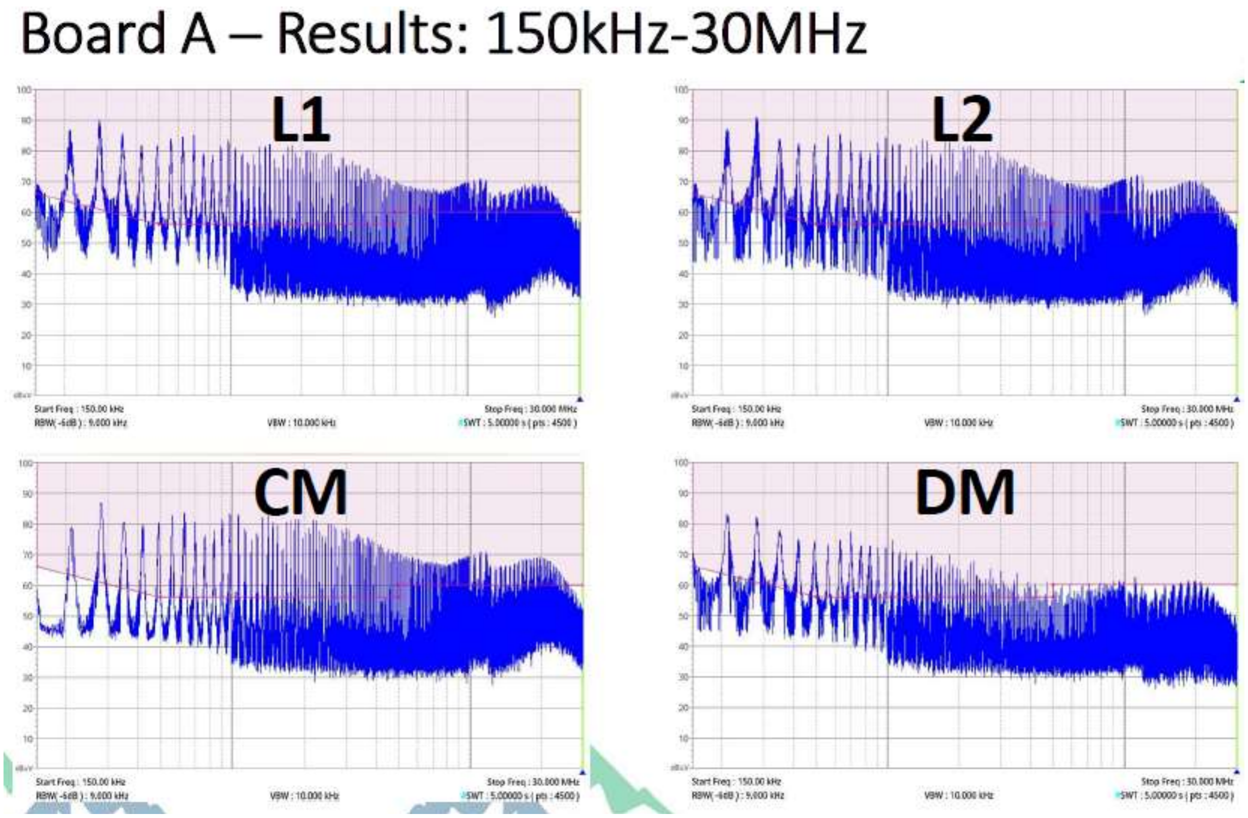

Board A – Results: 150kHz-30MHz

Fig. 6. Conducted EMI produced by power supply without any EMI components. L1 is the ac hot, L2 is the ac neutral, CM is the common-mode noise while DM is the differential-mode noise. This is the entire 150-kHz to 30.0-MHz frequency span.

In the next measurements, which involve Board B, the first series of components are added. These include the common-mode choke (a 47-mH inductor), and two Y rated capacitors: C_{Yf} (2.2 nF) and C_{Ye} (4.7 nF). Fig. 7 shows the four screen shots of L1, L2, DM and CM. If only commercial limits like those of FCC Part 15, Class A conducted were needed, this solution would marginally meets the limits. The common-mode choke is the single component with the greatest effect. The common-mode choke details are shown in Fig. 8.

The second component that contributes to the lowering of the EMI noise is the Y capacitor between the primary and the secondary called C_{Yf}. The C_{Yf} value of 2.2 nF together with the C_{Ye} of 4.7 nF to ground are critical to the earth ground leakage current. In the 2002 PET conference paper the capacitor between the primary and secondary was 3.3 nF or 3300 pF. This is important because the leakage current and ground-fault interrupt limit is 5.0 mAac per UL 943. Choosing a value greater than 3.3 nF results in a level of leakage current above the UL 943 limit.

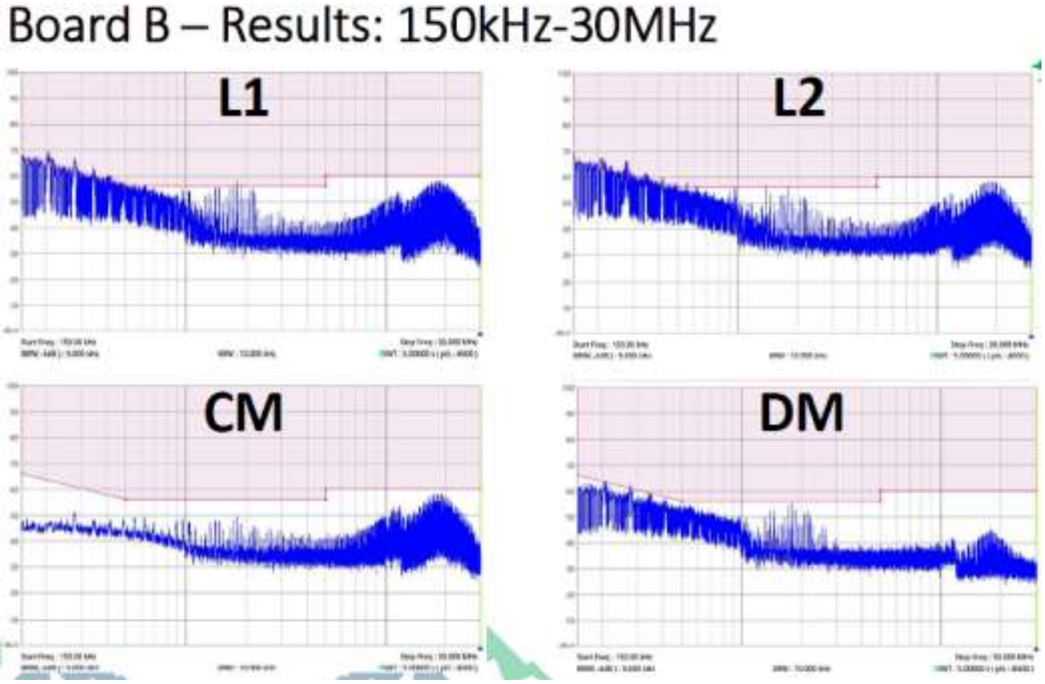

Board B – Results: 150kHz-30MHz

Fig. 7. Conducted EMI produced by the power supply with the common-mode choke (L_{CM} = 47-mH inductor) and two Y-rated capacitors, C_{Y1} (2.2 nF) and C_{Ye} (4.7 nF), installed for filtering.

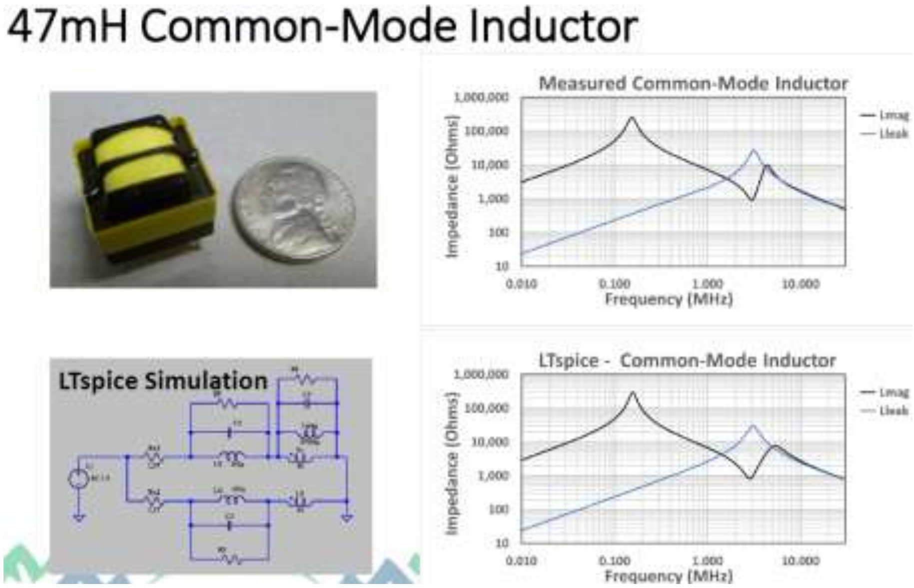

47mH Common-Mode Inductor

Fig. 8. The LTSpice model of the common-mode inductor, shown on the lower left with its values, is used to simulate the CM inductor's impedance, as shown in the graph on the lower right. These results agree with the measured results shown in the upper right graph.

Board C tests the effects of installing a common-mode choke with Y caps C_{Ya} and C_{Yb} after the CM choke. Measurements on this board are shown in Fig. 9. The unit passes the CM noise but does not affect the DM noise. The L1 and L2 limits are not met so additional components are needed.

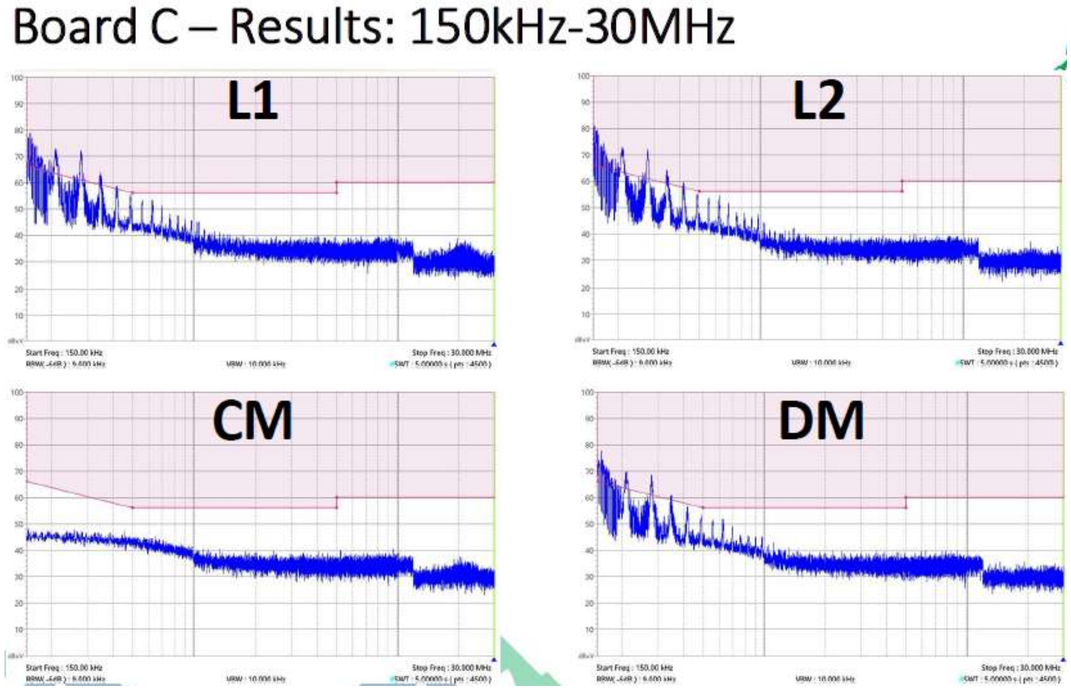


Fig. 9. Conducted EMI produced by the power supply with L_{CM}, C_{Yf} and C_{Ye}, plus Y-rated capacitors (C_{Ya} and C_{Yb} = 4.7 nF) after the choke. However, the L1 and L2 limits are still not met.

Board D tests the impact of adding the X capacitor C_{xa} to the choke and previously installed Y capacitors with the resulting EMI measurements shown in Fig. 10. In this case, the unit finally passes the FCC and EN 55022 Class B limits.

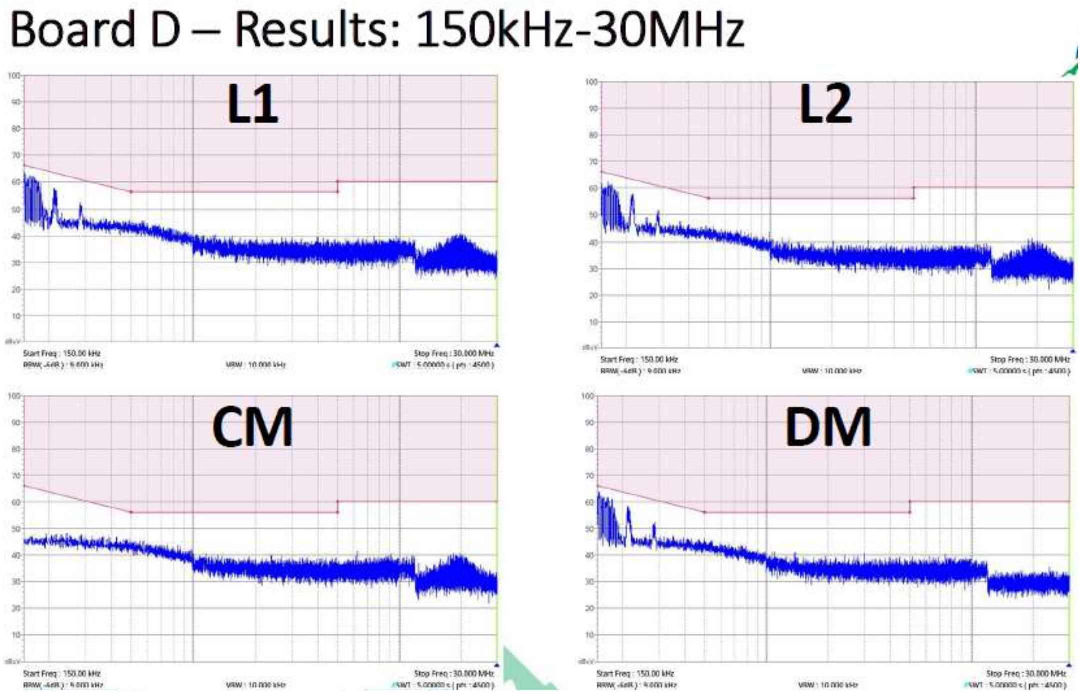


Fig. 10. Conducted EMI produced by the power supply with L_{CM}, C_{Yf}, C_{Ye}, C_{Ya} and C_{Yb} plus the X rated capacitor C_{Xa} = 0.15 µF installed. As seen here, the unit passes the FCC limits and the EN 55022 Class B limits.

With Board E, the last components—two Y-rated capacitors, C_{Yc} and C_{Yd}—are added to the EMI filter and the EMI results are shown in Fig 11.

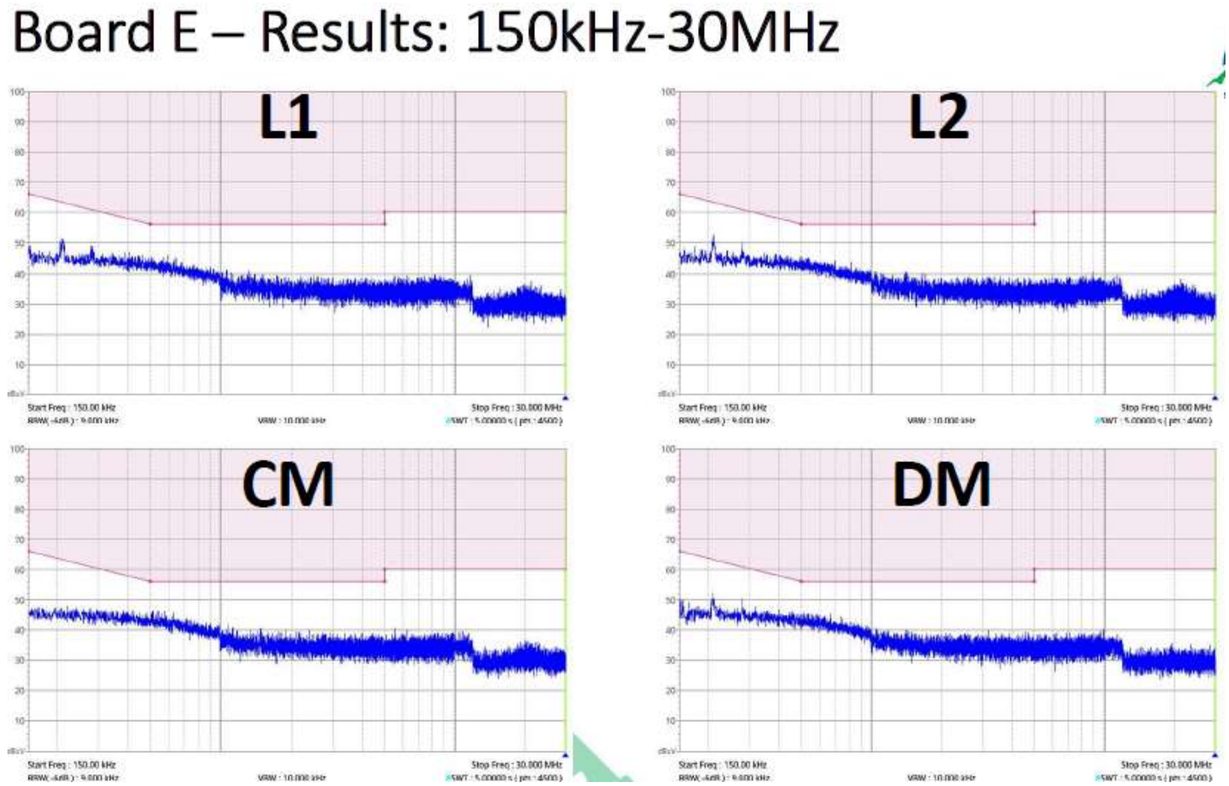

Board E – Results: 150kHz-30MHz

Fig. 11. Conducted EMI produced by the power supply with all the EMI components. In this measurement of Board E, L1, L2 and CM and DM pass the limits with additional margin versus Board D. The EMI filter used here differs only by the addition of C_{Yc} and C_{Yd}.

Meeting The FCC limits With A Two-Wire Line Cord

There are many application notes from various semiconductor manufacturers that provide EMI filters in their literature. However, the first document to demonstrate the effects of each EMI filter component was a paper given at the 2002 Power Electronics Technology Conference[4] in Chicago as discussed in this article.[4] The power supply designs used in the PET paper are shown in Figs. 12 and 13. The second publication that presented the effects was the Schutten and Li presentation[2, 3] at the IEEE EMC+SIPI conference.

Summary And Conclusion

The information presented in this article is intended to educate engineers on how to design a line-conducted EMI filter for low-wattage applications. Higher power levels still needs to be tested and presented, and so could be the basis for future work. Another set of issues arises with the use of dual or two common-mode inductors in series. More details are needed for the design and simulation of such designs.

Note that staying within EMI limits is not the only concern when designing the EMI input filter for an offline power supply. The leakage current is a critical safety item for the Y-rated capacitors to protected ground. The UL 943 limits are important for safety.

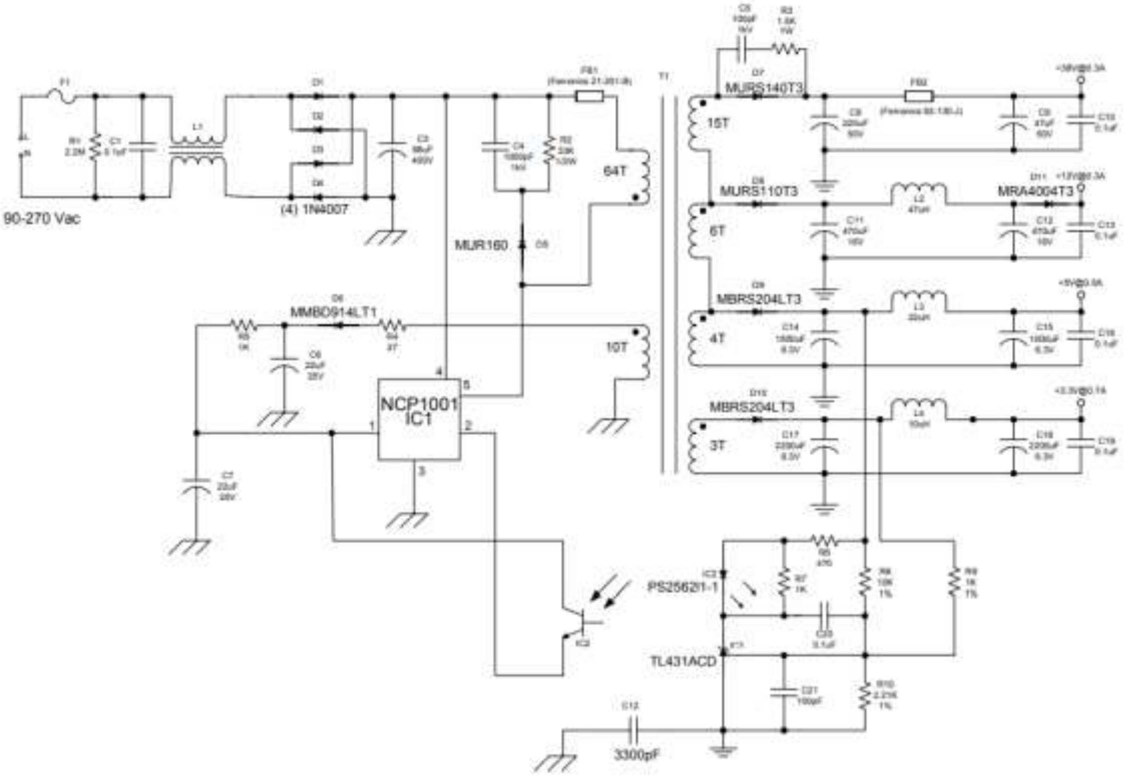


Fig. 12. The 20-W switched-mode power supply based on a fixed-frequency regulator. This design was used to demonstrate the influence of EMI filter components in the 2002 PET conference paper.

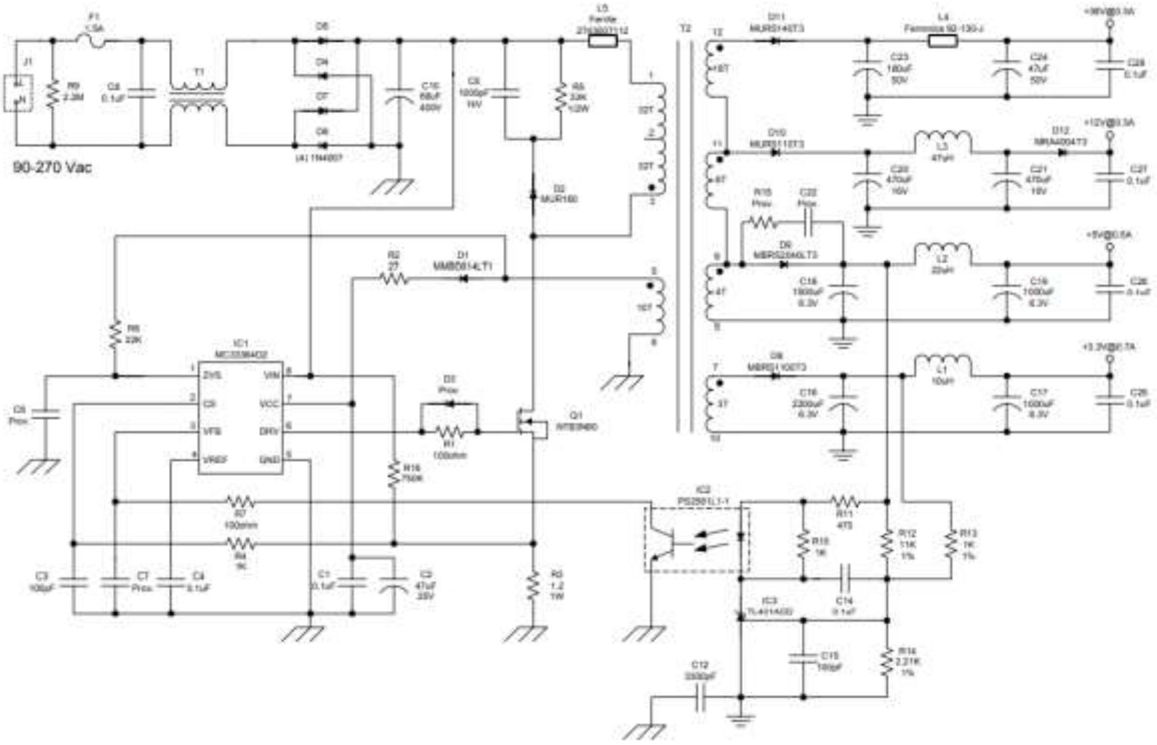


Fig. 13. The equivalent 20-W switched-mode power supply based on a critical conduction mode regulator. This was the second power supply design used by Spangler et al to demonstrate the impact of EMI filter components in the 2002 paper.

References

1. **"**EMC+SIPI Symposium Shares Valuable Tutorials Virtually**"** by Kevin Parmenter and James Spangler, How2Power Today, August 2020.

2. "EMI Noise Separation and Filter Design for a Switch-Mode Power Supply" by Michael Schutten and Cong Li, 2020 IEEE EMC+SIPI, Virtual Symposium, Experiments & Demo, Aug 10, 2020, 17 pages.

3. "EMC Fundamentals for Switch-Mode Power Converters" by Michael Schutten and Cong Li, 2020 IEEE EMC+SIPI, Virtual Symposium, Tutorials III, August 19, 2020, 89 pages.

4**.** "Solving EMI for Low Wattage Universal Input Power Supplies" by Jim Spangler, Dennis Jodlowski, Carl Walding, and Dave Pacholok, Power Electronics Technology Exhibition & Conference, Oct 30, 2002, D. E. Stephens Convention Center, Rosemont, IL.

About the Authors

Kevin Parmenter is an IEEE Senior Member and has over 20 years of experience in the electronics and semiconductor industry. Kevin is currently director of Field Applications Engineering North America for Taiwan Semiconductor. Previously he was vice president of applications engineering in the U.S.A. for Excelsys, an Advanced Energy company; director of Advanced Technical Marketing for Digital Power Products at Exar; and led global product applications engineering and new product definition for Freescale Semiconductors AMPD - Analog, Mixed Signal and Power Division.

Prior to that, Kevin worked for Fairchild Semiconductor in the Americas as senior director of field applications engineering and held various technical and management positions with increasing responsibility at ON Semiconductor and in the Motorola Semiconductor Products Sector. Kevin also led an applications engineering team for the start-up Primarion.

Kevin serves on the board of directors of the PSMA (Power Sources Manufacturers Association) and was the general chair of APEC 2009 (the IEEE Applied Power Electronics Conference.) Kevin has also had design engineering experience in the medical electronics and military electronics fields. He holds a BSEE and BS in Business Administration, is a member of the IEEE, and holds an Amateur Extra class FCC license (call sign KG5Q) as well as an FCC Commercial Radiotelephone License.

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For many years, he worked as a field applications engineer (FAE) for Motorola Semiconductor, On Semiconductor, Cirrus Logic, and Active Semiconductor, assisting customers in using semiconductors. He published numerous application notes and conference papers at a variety of conferences: APEC, ECCE, IAS, and PCIM. Topics included power factor correction, lighting, and automotive applications. As a FAE, he traveled internationally giving switch-mode power supply seminars in Australia, Hong Kong, Taiwan, Korea, Japan, Mexico, and Canada.

Jim has a master's degree from Northern Illinois University (NIU) and was a PhD candidate at Illinois Institute of Technology (IIT). He taught senior and first-level graduate student classes: Survey of Power Electronics, Fields and Waves, and Electronic Engineering at IIT and Midwest College of Engineering. Jim is a member of the IEEE: IAS, PELS, PES, PSES; the Illuminating Engineering Society (IES), and the Power Sources Manufacturers Association (PSMA) where he is co-chair of the Safety and Compliance Committee.

For further reading on power supply-related safety and compliance issues, see How2Power's special section on Power Supply Safety and Compliance.