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The Engineer's Guide To EMI In DC-DC Converters (Part 2): Noise Propagation And Filtering

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High switching frequency is the major catalyst for size reduction in the advancement of power conversion technology. It is essential to understand the EMI characteristics of high-frequency converters since the required EMI filter necessary for regulatory compliance typically occupies a significant portion of the overall system footprint and volume.

In part 2 of this series,[1] you'll gain an insight into dc-dc converter conducted EMI behavior by understanding sources and propagation paths for both the differential mode (DM) and common mode (CM) conducted emissions noise components. DM and CM noise separation from the total noise measurement is described, and a boost converter example is used to highlight the main CM noise conduction paths that exist in an automotive application.

DM And CM Conducted Disturbances

DM and CM signals represent two forms of conducted emissions. DM currents are generally referred to as symmetrical mode signals or transverse signals, whereas CM currents are also known as asymmetrical mode or longitudinal signals. A representation of DM and CM current paths in synchronous buck and boost dc-dc topologies is shown in Fig. 1. Y-capacitors C_{Y1} and C_{Y2} connected from positive and negative supply lines to earth ground are shown here to conveniently complete the common-mode current propagation path.[2]

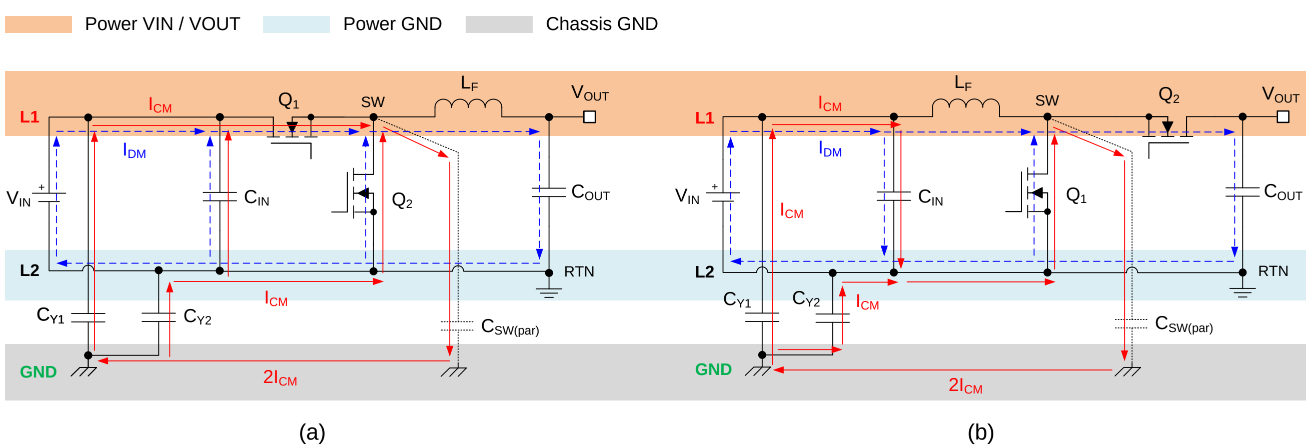


Fig. 1. DM and CM conducted noise paths for a synchronous buck converter (a) and a synchronous boost converter (b).

DM Conducted Noise

DM noise current, I_{DM}, is due to the intrinsic converter switching action and flows in opposite directions in the positive and return power lines, labeled as L1 and L2 in Fig. 1. DM emissions are "current driven" and associated with switching current (*di/dt*), magnetic fields and low impedance. DM noise generally flows in a small loop area, with a close and compact return path.

As an example, a buck converter operating in continuous conduction mode (CCM) draws a trapezoidal-shaped current rich in harmonics. These harmonics present as noise on the power lines. The buck converter's input capacitor, designated C_{IN} in Fig. 1, helps to supply these higher-order current harmonics, but due to the capacitor's parasitic non-idealities—equivalent series inductance (ESL) and equivalent series resistance (ESR)—some harmonics inevitably appear in the supply current as DM noise, even after a practical EMI filter stage has been added.

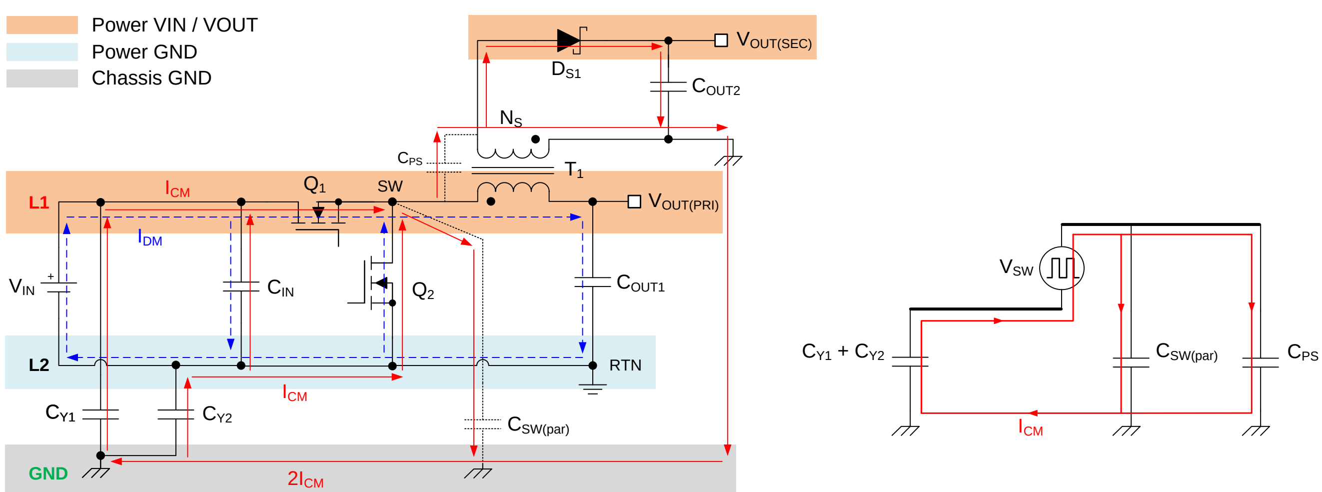
CM Conducted Noise

On the other hand, CM noise current, I_{CM}, flows in the earth GND wire and returns via both power lines L1 and L2. CM emissions are "voltage driven" and associated with high slew rate voltage (*dv*/*dt*), electric fields and high impedance. In the case of a nonisolated dc-dc switching converter, the CM noise is mainly due to the high *dv*/*dt* at the switch node (SW) causing a displacement current that couples to the GND system through the parasitic capacitance associated with the MOSFET case, heatsink and switch node trace. Coupling capacitance associated with long cabling from a converter's input or output may also represent a CM noise path.

The CM current in Fig. 1 is depicted as returning via the Y-caps of the input EMI filter, C_{Y1} and C_{Y2}. The alternative return path is through the 50-Ω measuring impedance of the LISN setup (discussed in part 1[1]), obviously undesirable. Even though CM current is considerably less in magnitude than DM current, it is more difficult to deal with as it typically flows in a large conducting loop area, thus acting as an antenna and representing a possible mechanism for increased radiated EMI.

Shown in Fig. 2a are the DM and CM conduction paths for a Fly-Buck, or isolated buck, converter. A CM current flows to the secondary side through the lumped interwinding capacitance of transformer T_1 (designated C_{PS} in Fig. 2) and returns via the earth GND connection. The simplified equivalent circuit for CM propagation is shown in Fig. 2b.

In practical dc-dc converters, component parasitics such as MOSFET output capacitance "C_{OSS}," rectifier diode junction capacitance "C_D," equivalent parallel capacitance (EPC) of the main inductor winding, and ESL of the input and output capacitors all influence the voltage and current waveforms as well as the CM noise disturbance. This will be discussed in further detail in part 3 of this article series.



(a) (b)

Fig. 2. Fly-buck isolated converter DM and CM conducted noise propagation paths (a); CM equivalent circuit (b).

Noise Source And Propagation Path

As outlined in part 1, dc-dc converter conducted emissions over a regulatory bandwidth of 150 kHz to 30 MHz for CISPR 32, and an even wider 150 kHz to 108 MHz frequency range for CISPR 25, are measured with respect to the *total noise* voltage or "unsymmetric" disturbance relative to earth GND across a 50-Ω LISN resistor for each power line.[2]

The phenomenon of EMI noise generation, propagation, and measurement for a dc-dc converter can be modeled as shown in Fig. 3.[2] The noise source voltage is denoted as V_N, and the noise source and propagation path impedances are denoted as Z_S and Z_P, respectively. The high-frequency equivalent circuit of the LISN and EMI receiver is simply two 50-Ω resistors.

Also illustrated in Fig. 3, the respective DM and CM noise voltages, V_{DM} and V_{CM}, are derived from the total noise voltage measured for each power line, V_1 and V_2. The DM or "symmetric" voltage component is defined as half the vector difference of V_1 and V_2 whereas the CM or "asymmetric" voltage component is half the vector sum of V_1 and V_2.[3] Note the possible 6-dB discrepancy in the common definition of V_{DM} provided here vis-à-vis what is specified in the CISPR 16 standard.

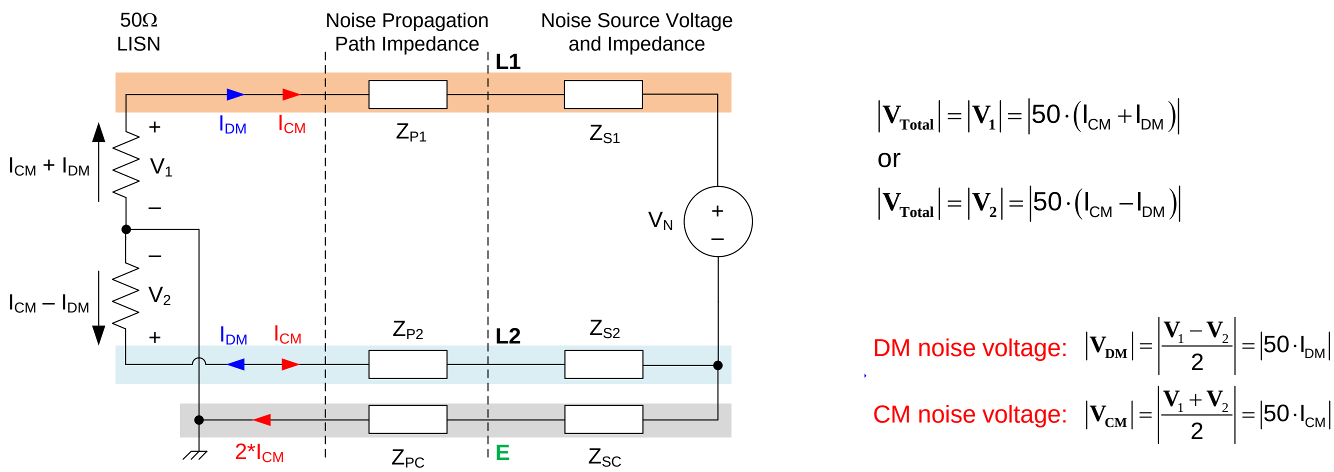


Fig. 3. Conducted EMI emissions model for a dc-dc converter with noise source, noise propagation path and LISN equivalent circuit.

The CM noise source impedance is mostly capacitive and Z_{CM} decreases with frequency. Meanwhile, the DM noise source impedance is typically resistive and inductive whereby Z_{DM} increases with frequency.

One way to reduce the level of conducted noise is by ensuring that less noise is generated by the noise source itself. For the noise propagation path, we seek to modify the impedance by filtering and other means to reduce the corresponding current flow. For example, CM noise reduction in a buck or boost converter entails decreasing of the SW node dv/dt (the noise source), increasing impedance by decreasing the parasitic capacitance to GND, or by filtering using Y-capacitors and/or a CM choke. A detailed classification of EMI mitigation techniques will be discussed in part 4 of this article series.

DM And CM EMI Filtering

Passive EMI filtering is the most common approach for EMI noise mitigation. As the name suggests, these filters use only passive components. The design of such filters for use in power electronics is particularly challenging, since the filters are terminated with varying noise source (switching converter) and load (power line) impedances.[3,4]

Fig. 4a shows a conventional π-stage EMI input filter as well as rectification and transient voltage clamping functions for EMC protection for a dc-dc converter supplied by a dc or ac input. The LISN high-frequency equivalent circuit from part 1 of this article series is also included in Fig. 4.

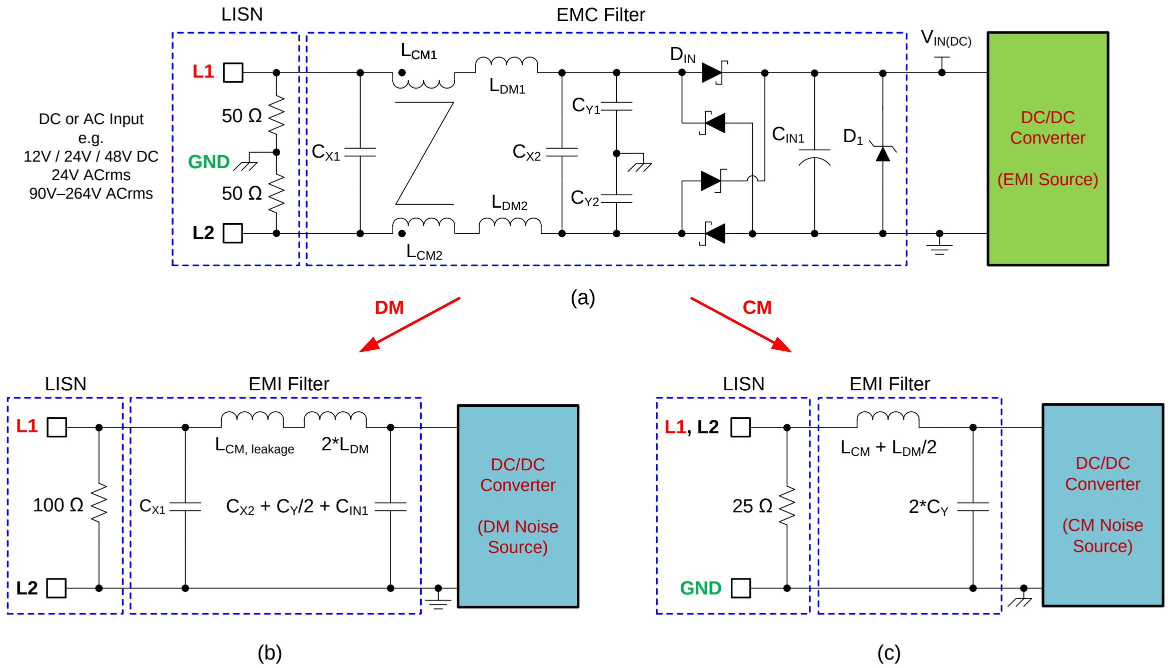


Fig. 4. Conventional EMC input filter (a) including equivalent circuits for the DM (b) and CM (c) filter sections.

The two CM windings of a typical EMI filter are coupled, and the CM inductances of the two windings are L_{CM1} and L_{CM2}. The DM inductances L_{DM1} and L_{DM2} are the leakage inductances of the two coupled CM windings and may also include discrete DM inductors. C_{X1} and C_{X2} are DM filter capacitors, and C_{Y1} and C_{Y2} are CM filter capacitors.

The EMI filter is decoupled into its equivalent DM and CM equivalent circuits to simplify its design. The DM and CM attenuation of the filter can then be analyzed, respectively. This decoupling is based on the assumption that the EMI filter has perfectly symmetric circuit structures. In a symmetrical filter implementation, it is assumed that component values $L_{CM1} = L_{CM2} = L_{CM}$, $C_{Y1} = C_{Y2} = C_Y$ and $L_{DM1} = L_{DM2} = L_{DM}$. The printed circuit board (PCB) layout is also assumed perfectly symmetric. The DM and CM equivalent circuits are derived in Fig. 4b and Fig. 4c, respectively.[5]

Strictly speaking, however, perfect symmetry cannot apply in a practical case, so the DM and CM filters cannot be totally decoupled. As a result, DM noise can transform into CM noise and vice versa due to asymmetries. In general, unbalance associated with converter noise sources and EMI filter parameters can result in such mode transformations.[6]

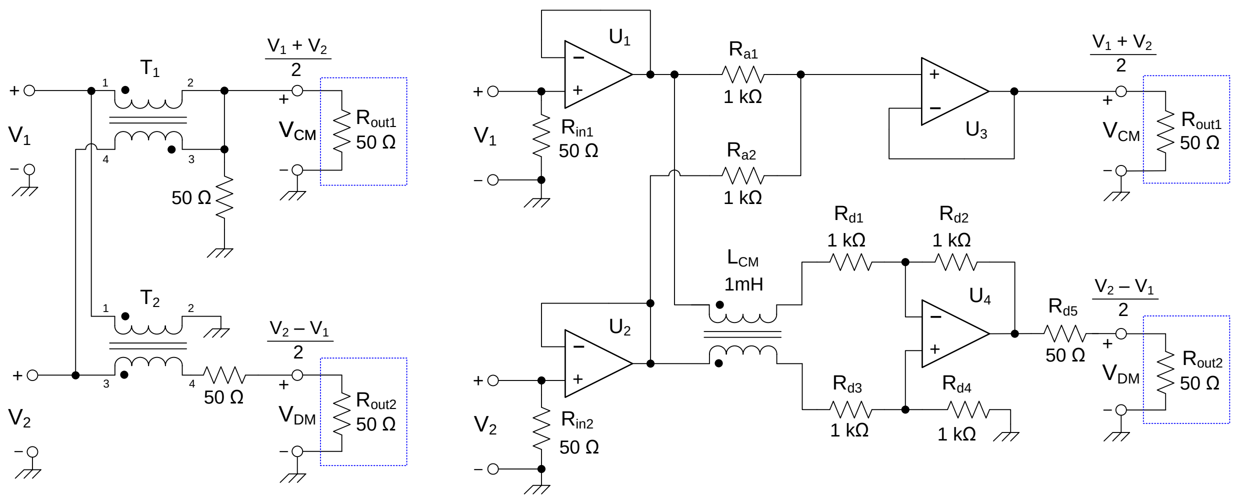
DM And CM Noise Separation

Initial measurements of conducted EMI often reveal insufficient EMI filter attenuation. For proper EMI filter design, it is imperative to individually investigate the DM and CM noise voltage components of the conducted emissions generated by the equipment under test (EUT). Treating DM and CM components separately helps to recognize and troubleshoot the relevant EMI source and to streamline the EMI filter design process.

As highlighted in the previous section, the EMI filter employs essentially different filter components to suppress both DM and CM emissions. Within this context, one common approach for a diagnostic inspection is to separate the conducted noise into its DM and CM noise voltages.

Passive and active realizations of a DM and CM separator circuit that facilitate direct and simultaneous measurement of DM and CM emissions are presented in Fig. 5. The passive separator circuit[5] in Fig. 5a uses wideband RF transformers, such as the SWB1010 series from Coilcraft, with characteristic impedance Z_O of 50 Ω and 100 Ω for T_1 and T_2, respectively, to achieve acceptable separation capabilities over the frequency range of the EMI sweep. A 50-Ω resistor in series with the input impedance of the EMI receiver at the DM output port achieves a divide-by-two function according to the expression for V_{DM} provided in Fig. 3.

An active separator circuit[7] using low-noise, high-bandwidth operational amplifiers is presented in Fig. 5b. U_1 and U_2 realize an ideal input impedance matrix for the LISN outputs, while U_3 and U_4 provide the CM and DM voltages, respectively. L_{CM} is a CM line filter, such as Würth Elektronik 744222, at the input to differential amplifier U_4 that increases the CM rejection ratio of the DM result (CMRR → −∞ dB) and minimizes CM-DM cross-coupling.



(a) (b)

Fig. 5. Passive (a) and active (b) circuit realizations for DM and CM noise separation.

Practical Circuit Example—Automotive Synchronous Boost Converter

Consider the synchronous boost converter as shown in Fig. 6. The circuit is commonly used in automotive applications as a pre-boost regulator that maintains the battery voltage supply during cold-crank or transient undervoltage conditions.[8]

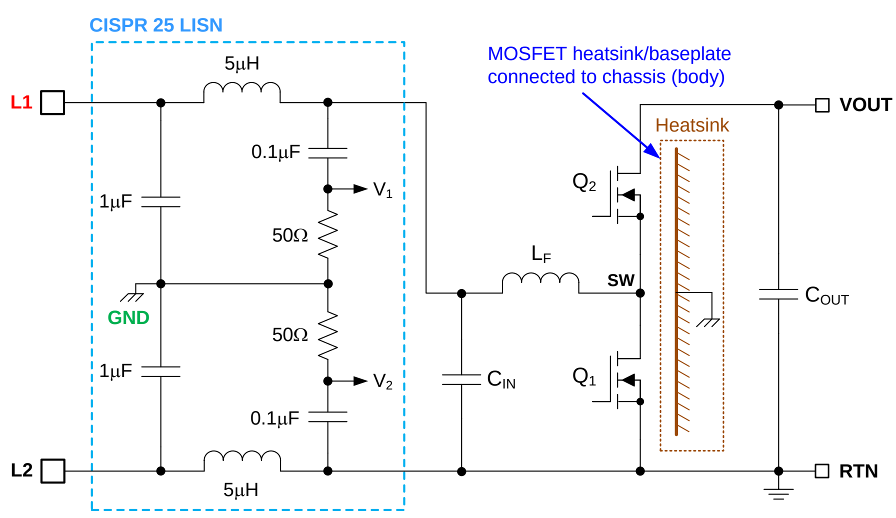


Fig. 6. Automotive synchronous boost converter with 50-Ω/5-µH LISN for CISPR 25 EMI testing.

A MOSFET heatsink is directly attached to the vehicle's chassis ground to improve the converter's thermal performance and reliability, but at the expense of common-mode EMI performance. The schematic in Fig. 6 includes the boost converter together with two CISPR 25 recommended LISN circuits connected at the L1 and L2 input lines.

To consider the boost converter CM noise propagation paths, MOSFETs Q_1 and Q_2 are replaced by their equivalent ac voltage and current sources in Fig. 7.[9] The parasitic component elements associated with boost inductor L_F, input capacitor C_{IN}, and output capacitor C_{OUT} are also depicted. In particular, $C_{RL\text{-}GND}$ is the parasitic capacitance from load circuit to chassis GND, including contribution from long load lines and cabling as well as the downstream load configuration (for example, an isolated converter with secondary side output grounded to chassis or a motor drive system load with large metallic case bonded to chassis).

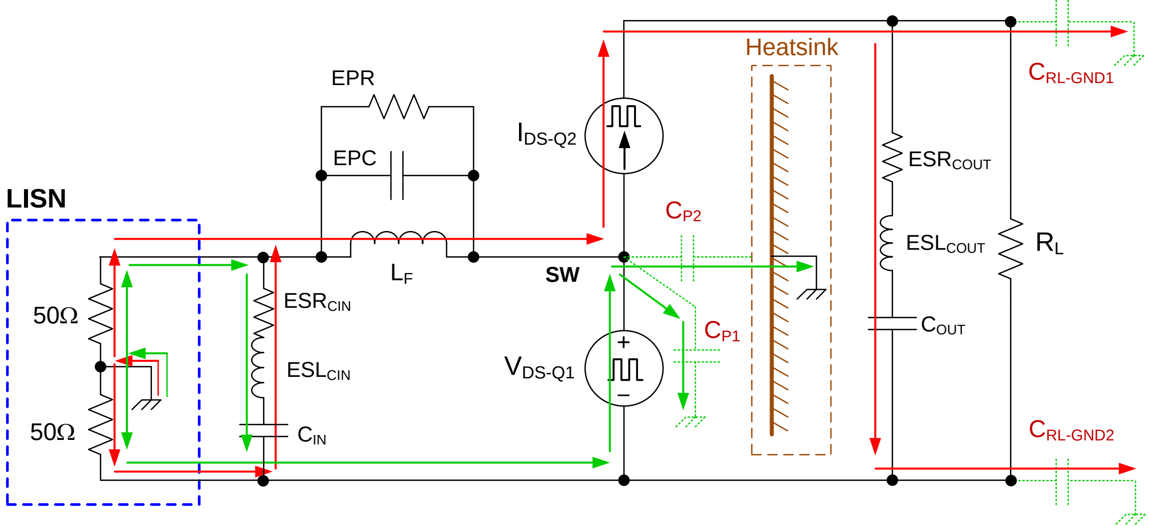


Fig. 7. High-frequency equivalent circuit for a synchronous boost topology with LISN. Only the CM current paths that flow in LISN are relevant for CM emission measurements.

The rising and falling edges of the drain-to-source switching (SW node) voltage represent the dominant CM noise source. C_{P1} and C_{P2} represent the effective parasitic capacitances from SW to chassis and SW to heatsink, respectively. Fig. 8 shows the simplified CM noise equivalent circuit for the case where the SW node capacitive (e-field) coupling is the dominant CM propagation path.

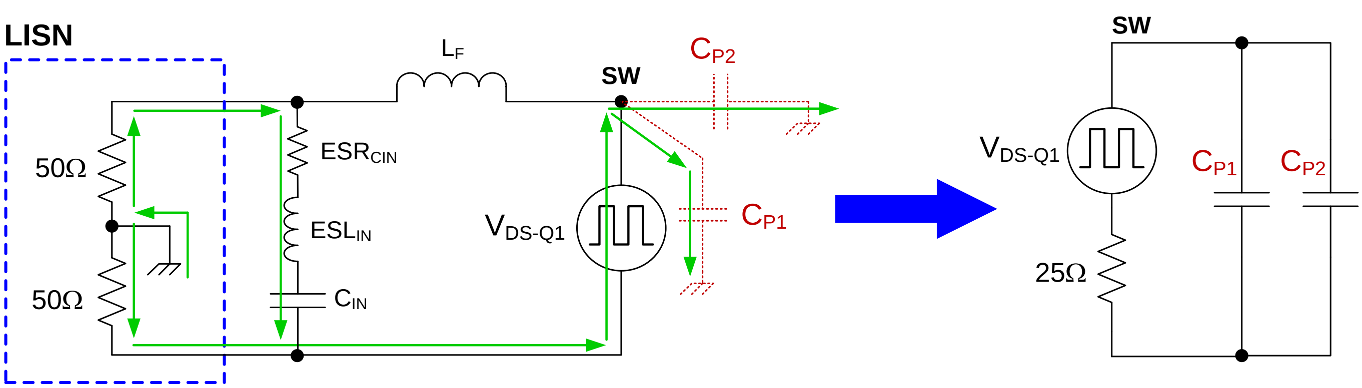


Fig. 8. Simplified CM equivalent circuit derived from Fig. 7 for the synchronous boost circuit with LISN connected.

Summary

An explanation of conducted EMI propagation modes was provided here, including capacitive (electric field) and inductive (magnetic field) coupling related to high *dv/dt* and *di/dt* switching. The relevant propagation paths for DM and CM currents in various power stage topologies were described. Most important, the separation of DM and CM emissions during EMI testing was emphasized as this helps designers to recognize and troubleshoot the relevant EMI source and to streamline the EMI filter design process. A case study highlighted the CM EMI signature associated with an automotive synchronous boost converter.

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About The Author

Timothy Hegarty is an applications engineer for Power Products Solutions at Texas Instruments. With 20 years of power management engineering experience, he has written numerous conference papers, articles, seminars, white papers, application notes and blogs.

Tim's current focus is on enabling technologies for high-frequency, low-EMI, isolated and nonisolated regulators with wide input voltage range, targeting industrial, communications and automotive applications in particular. He is a senior member of the IEEE and a member of the IEEE Power Electronics, Industrial Applications and EMC Societies.

For more information on EMI, see How2Power's Power Supply EMI Anthology. Also see the How2Power's Design Guide, locate the Design Area category and select "EMI and EMC".