Polarity of coils for DC-DC converters

Considerations for Power Inductors: How Flux Orientation Can Reduce Radiated Emission

Introduction

Power Inductors are a part of the power stage of switch mode power supplies (SMPS) such as non-isolated DC-DC buck converters. Power traces from the printed circuit board (PCB), power supply lines and power inductors, also called coils, cause electromagnetic interference (EMI) noise such as radiated emission. The leakage field of the coil affects the overall radiated emission of an SMPS. Manufacturers of coils define the relationship between the directions of the current flow and the magnetic flux and are developing shielded coils to reduce radiated emission from the SMPS. Therefore, paying attention to coil orientation is essential during the assembly process of a coil on a PCB. This application note examines the radiated emission caused by coils, depending on their polarity, in a DC-DC converter.

Leakage flux in power inductors

A coil consists of an insulated wire wound around a core made of high-permeability material. An electrical current flowing through a wire causes a magnetic field circling the wire in clockwise orientation with the direction of the current. When a wire is wound on a magnetic core and current is applied, the magnetic flux refluxes inside the core and causes a magnetic stray field around the coil.

Unshielded coils have an open drum core with an open magnetic path. When an unshielded coil is used, the magnetic flux leaves the core and becomes a leakage flux, which forms a loop that returns to the core. The magnetic flux spreads widely around the coil, as shown in Figure 1.

Shielded coils, which are more expensive, feature a box made of the magnetic material used for the core. This box covers and hides the drum core and windings, which allows the magnetic flux to leave an air gap between the pot core and the shielding box. This is shown in Figure 2.

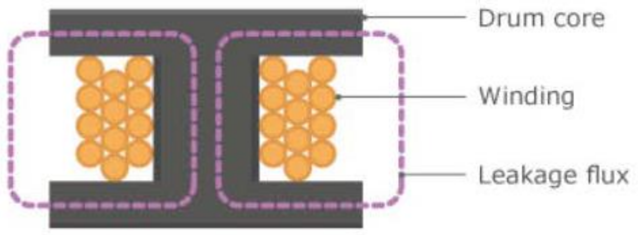

FIGURE 1: MAGNETIC FLUX IN UNSHIELDED DRUM CORE COILS

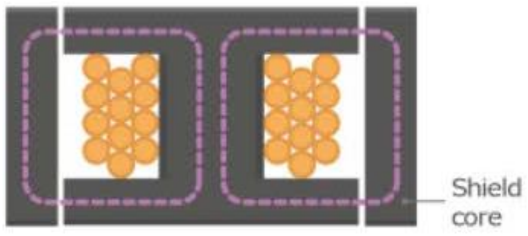

FIGURE 2: MAGNETIC FLUX IN SHIELDED DRUM CORE COILS

Since the magnetic flux refluxes inside the drum core and the shield core, the magnetic path inside the coil is closed and the leakage flux is reduced.

However, magnetic shielding does not always provide complete encapsulation, and flux can leak from the air gap or terminal of the junction between the shield material and the drum core.

Magnetic flux depends on winding direction

The direction of the magnetic flux in the core and the surrounding H-field depend on the current flowing through the wire from the coil.

With increasing current, the leakage flux and H-field increase in the coil.

Figure 3 shows a coil with an orientation of 0°, the resulting magnetic field direction, and the magnetic flux. The current flows through the coil from the side which features a “Polarity mark”.

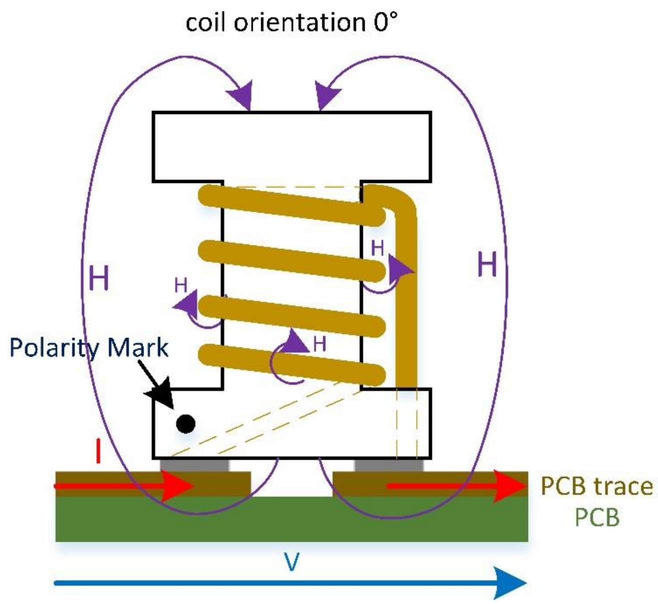

FIGURE 3: MAGNETIC FLUX AND H FIELD WITH COIL ORIENTATION OF 0°

In this case, the magnetic flux leaves the drum core from the bottom of the coil and becomes a leakage flux, which forms a loop that returns to the top of the drum core.

When rotating the coil in the circuit on a PCB by 180°, this changes the current flow through the coil as well as the H-field surrounding the wire and coil. The resulting magnetic flux through the drum core of the coil also changes direction.

Figure 4 shows a coil with an orientation of 180° and the resulting magnetic field direction, as well as the magnetic flux. Now the current flows through the coil from the side without the “Polarity mark”.

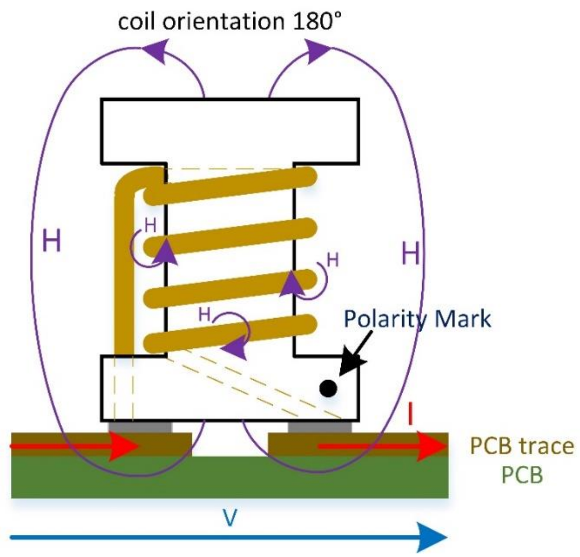

FIGURE 4: MAGNETIC FLUX AND H FIELD WITH COIL ORIENTATION OF 180°

This picture shows a different direction for the H-field and flux, caused by the changed direction of the DC current flow though the coil wire.

Here, the magnetic flux leaves the drum core from the top of the coil and becomes a leakage flux, forming a loop that returns to the bottom of the drum core.

Magnetic field of power inductors on PCB

A magnetic field surrounding the coil on a PCB correlates with the direction of the magnetic flux through the coil. The leakage flux also depends on the coil structure and size. Coils of smaller size have reduced leakage flux.

Changing the polarity of a coil by rotating it by 180° on the PCB in an electronic circuit of SMPS will change the pattern of the current direction through the coil's wire, which in turn leads to a change in direction of the magnetic flux inside the core of the coil.

Figure 5 shows the simulated magnetic field distribution on the PCB surface, according to the polarity of the coil.

The red color indicates that the magnetic field strength is higher and the blue color indicates that the magnetic field strength is lower.

If the leakage magnetic flux direction of the coil changes, then the degree to which the wiring pattern interferes with the magnetic field changes as well. The polarity of the magnetic field around the coil is altered.

When two coils are placed close together on a PCB, magnetic flux leaks from each coil, affecting the other coil. Therefore, the current flow through the coil from start to end of the winding has to be considered for both coils.

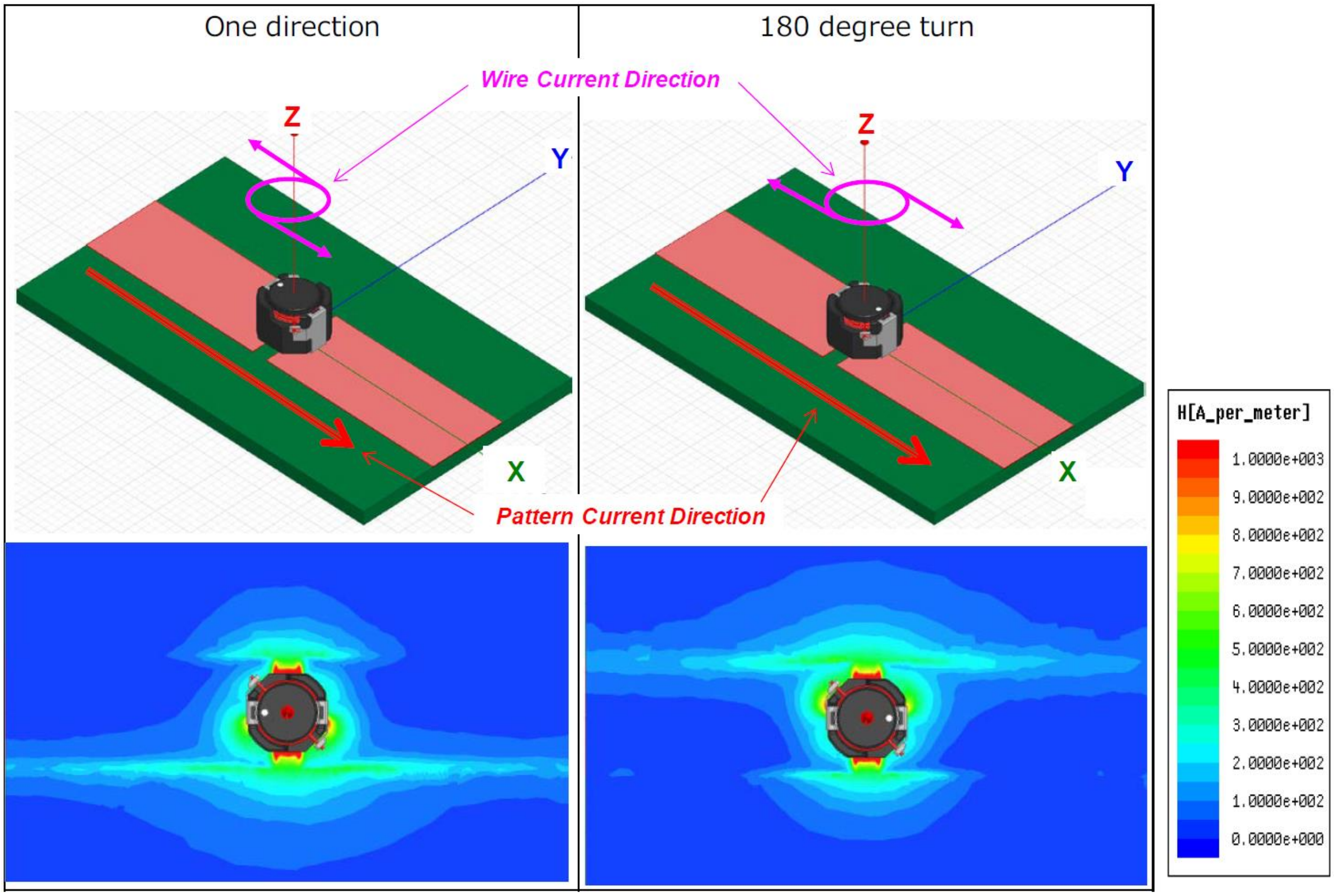

FIGURE 5: MAGNETIC FIELDS DEPEND ON POLARITY

Near-H-field measurement system

Measurements are performed in order to analyze the magnetic field of coils near an H field and to visualize leakage flux in 3D graphics.

The basic configuration of the system which is used to measure a coil near an H field, including its visualization, is shown in Figure 6.

A spectrum analyzer converts the data of the obtained time waveform into a spectrum waveform, which is then displayed on the monitor in the form of 3D graphics.

The horizontal H-field has a directionality, and the electromotive force of the loop antenna is maximized when the loop antenna surface and magnetic flux cross at a right angle. Therefore, as for the horizontal magnetic field, the probe is rotated in four directions (every 45 °) and the maximum voltage is measured.

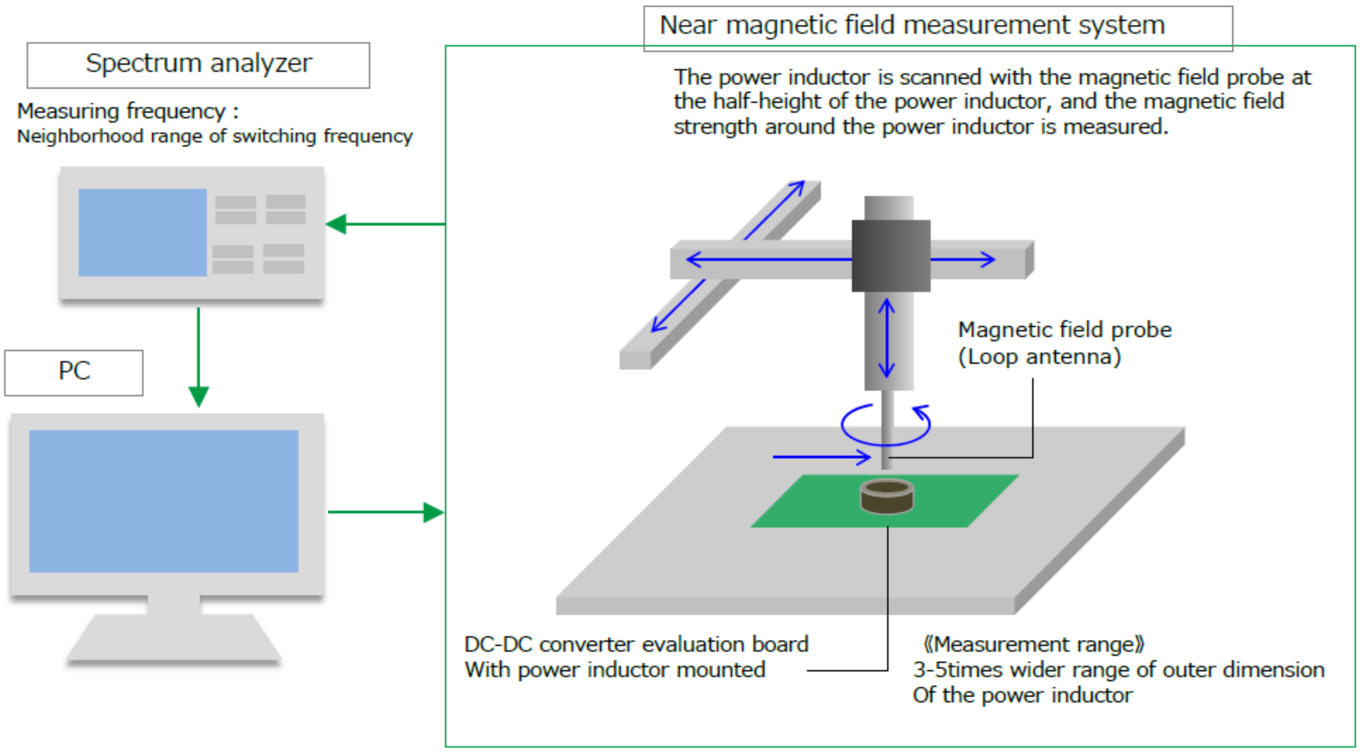

FIGURE 6: TEST SETUP OF NEAR H FIELD MEASUREMENT SYSTEM

The coil mounted on the evaluation board of the DC-DC converter is scanned with an H-field probe, which is equipped with a small loop antenna, at half the height of the coil. The magnetic field strength around the coil is measured in a defined frequency band according to the switching frequency of the DC-DC converter.

Near-H-field measurement

In the next example, a ROHM Semiconductor evaluation board featuring the automotive DC-DC converter IC BD9P235EFV, with a 10µH mounted CLF-NI-D series coil from TDK, is analyzed for its H-field dependency on the polarity of the coil. This DC-DC converter operates at a switching frequency of 2.2 MHz.

Figure 7 shows the test result of the horizontal near-magnetic-field analysis from the evaluation board's top side in a frequency range from 1 MHz to 10 MHz.

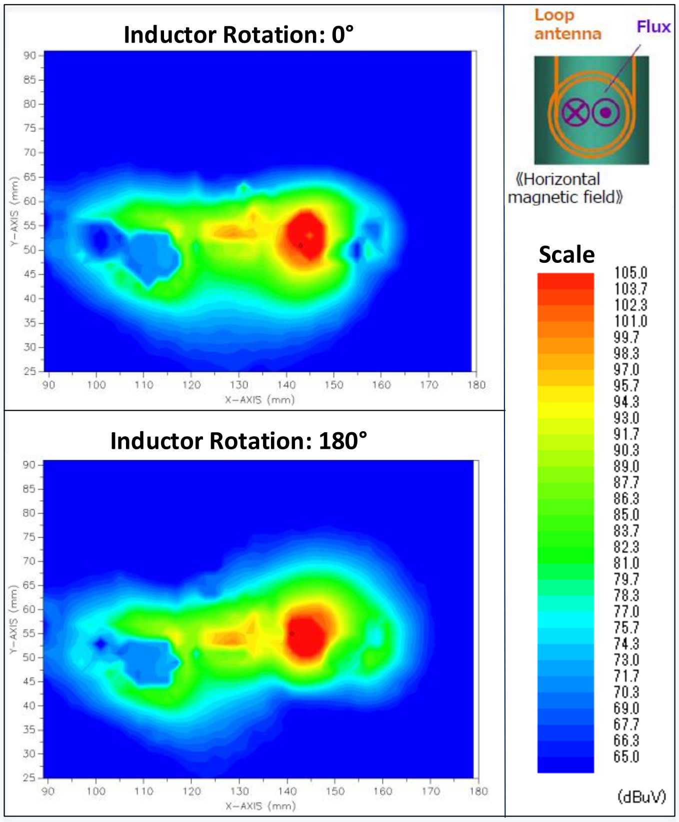

FIGURE 7: HORIZONTAL H FIELD OF THE COIL

The highest magnetic flux value of 105 dBµV shows at the coil's center.

Now the coil is rotated by 180° in order to analyze the magnetic field dependency on the polarity of the coil in the DC-DC converter.

The measurement results show a change in the area of the magnetic field, but the intensity remains unchanged. The magnetic flux is still around 105 dBµV at the coil's top center.

In both test cases, the magnitude of the magnetic flux outside of the coil is around 90 dBµV.

Near-field analysis in the frequency domain

The high di/dt current through a coil is inherently discontinuous and alternates with the switching frequency of the DC-DC converter. Copper windings around the core cause a magnetic loop inside the coil. Shielded coils have an air gap between the drum core and the shielding box, where the leakage magnetic flux flows. The magnetic field in the gap between the drum core and the coil's shielding is indicated by a red circle in the magnetic field simulation in figure 5. Leakage flux causes electromagnetic noise in the near field over a narrow band. The magnetic field strength varies depending on leakage flux, coil current, wire loop size and distance from the coil. A spectrum analyzer and a near-field H probe can be used to analyze the magnetic field of a coil at the DC/DC converter in the frequency domain.

Figure 8 shows the magnetic field around TDK's CLF-series coil on the BD9P235EFV evaluation board with a coil orientation of 0° in a frequency range of 150 kHz to 30 MHz.

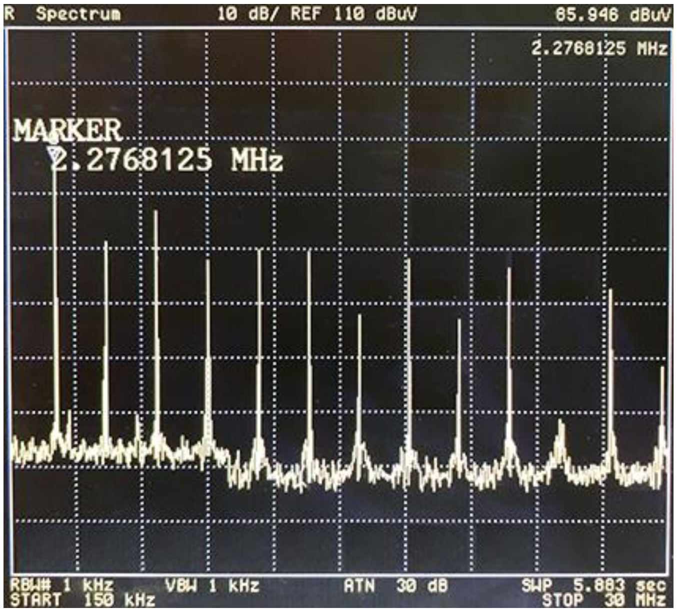

FIGURE 8: MAGNETIC FIELD AROUND THE COIL, 150 KHZ TO 30 MHZ, WITH 0° ROTATION

In the fundamental oscillation, the highest peak is 86 dB(µV) at the DC-DC converter's switching frequency of 2.2 MHz. Further harmonic peaks will drop at a higher frequency range.

The orientation of the coil has an impact on the absorption of the magnetic field. Changing the polarity of the coil will change the amplitude of the absorbed magnetic field as well. Figure 9 shows the difference made by changing the polarity of the coil by 180°.

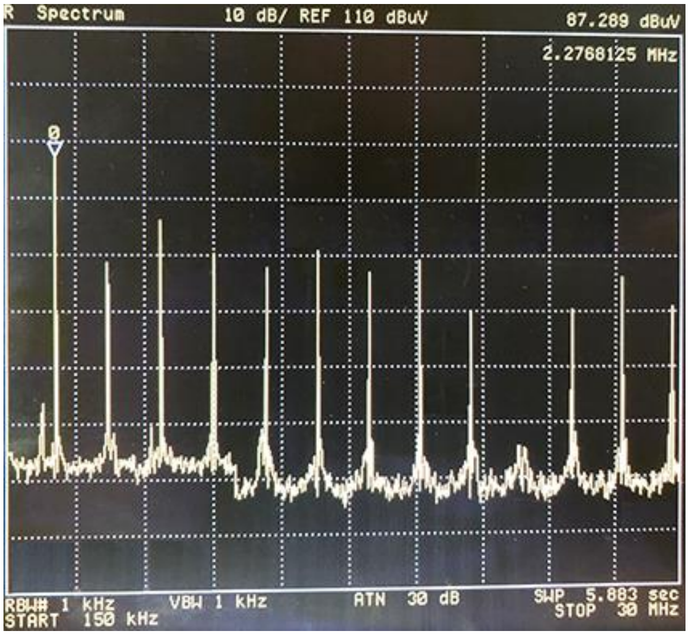

FIGURE 9: MAGNETIC FIELD AROUND THE COIL, 150 KHZ TO 30 MHZ, WITH 180° ROTATION

In the fundamental oscillation, the highest peak is slightly increased to 87 dB(µV). Further harmonics are increased by around 2 dB(µV) in their amplitude.

Since the direction of the leakage flux from the coil differs depending on the mounting direction of the coil, the degree of interference with the magnetic field generated from the board also differs, as well as the noise level.

The causes of magnetic fields around coils are complex already, but in higher frequency ranges, the switch node poses an additional impact on the magnetic field. The magnetic field is dominant in the frequency range from 30 MHz to 500 MHz, where ringing is represented at the switch node. Switch node ringing usually occurs between 40 MHz and 300 MHz, where the frequency depends on the DC-DC converter's switching frequency and the PCB's parasitics, thus this varies from application to application.

Figure 10 shows a magnetic field on the same evaluation board with a coil orientation of 0° in a frequency range of 30 MHz to 500 MHz.

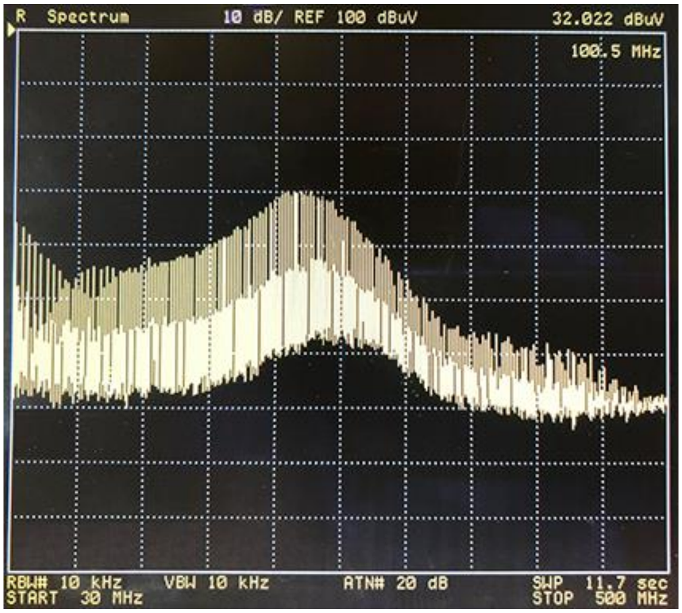

FIGURE 10: MAGNETIC FIELD AROUND THE COIL, 30 MHZ TO 500 MHZ, WITH 0° ROTATION

In the frequency range shown in Figure 10, the magnetic field is at its highest in the range of oscillations between 60 MHz and 90 MHz with the highest peak at 70 dB(µV) and decreasing with frequency.

Figure 11 shows the difference made by changing the polarity of the coil by 180° in a frequency range of 30 MHz to 500 MHz.

Changing the polarity of the coil results in the magnetic field increasing by around 5 dB(µV) in the lower frequency range from 30 MHz to 50 MHz, and the amplitude decreasing by around 10 dB(µV) at the frequency of switch node ringing.

The coil connected to the switch node affects the electric field where high dv/dt voltages alternate. The resulting E field can be measured with a spectrum analyzer and an E-field probe in the near field.

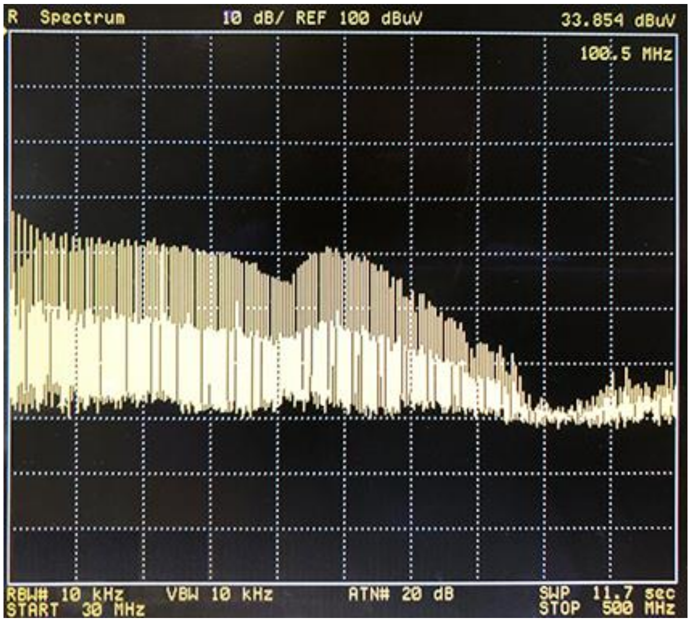

FIGURE 11: MAGNETIC FIELD AROUND THE COIL, 30 MHZ TO 500 MHZ, WITH 180°ROTATION

Figure 12 shows the electric field at the top of the coil on the same evaluation board with a coil orientation of 0° in a frequency range of 150 kHz to 30 MHz.

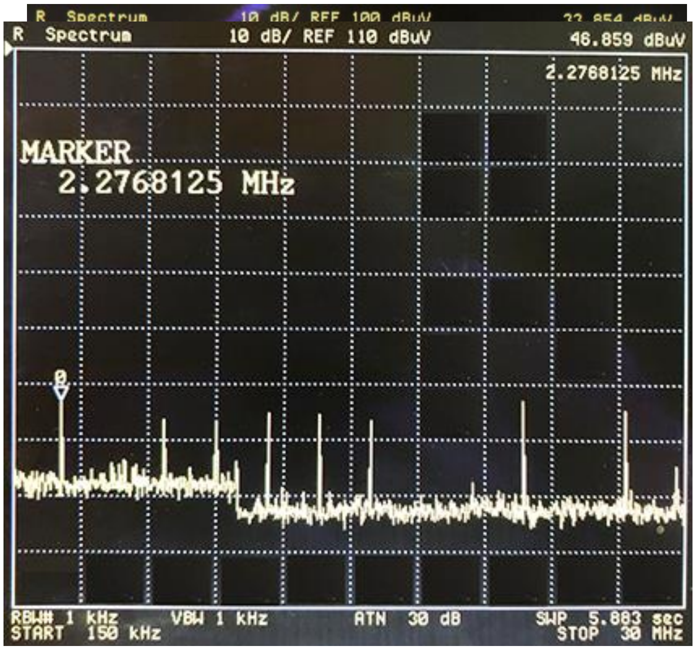

FIGURE 12: ELECTRIC FIELD AT THE TOP OF THE COIL, 150 KHZ TO 30 MHZ, WITH 0°ROTATION

Changing the polarity of the coil will change the amplitude of the electric field as well. The direction of the inductor is specified by the manufacturer. Figure 13 shows the electric field at the top of the coil on the same evaluation board with a polarity of 180° in a frequency range of 150 kHz to 30 MHz.

The highest peak still shows in the fundamental oscillation but is increased by 12 dB(µV). Further harmonics are increased, too.

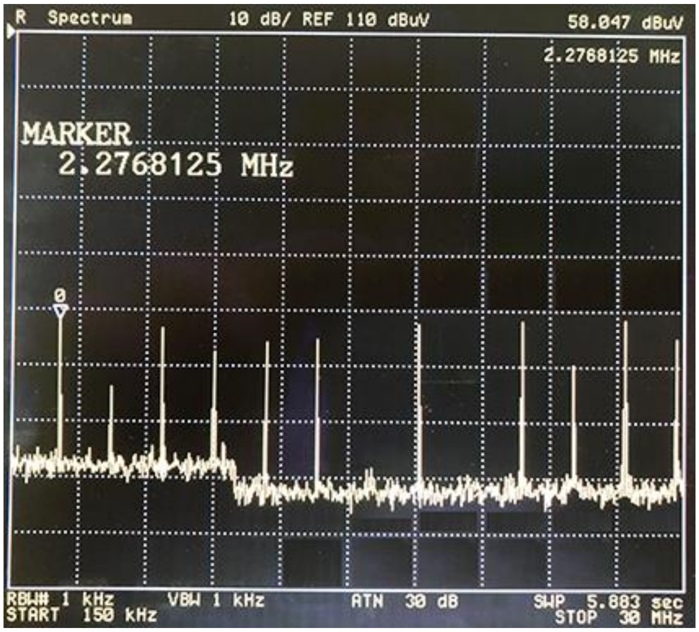

FIGURE 13: ELECTRIC FIELD AT THE TOP OF THE COIL, FROM 150 KHZ TO 30 MHZ, WITH 180°ROTATION

The electric field in higher frequency ranges is influenced by ringing at the switch node. Figure 14 shows the electric field of a coil on the same evaluation board with a coil orientation of 0° in a frequency range of 30 MHz to 500 MHz.

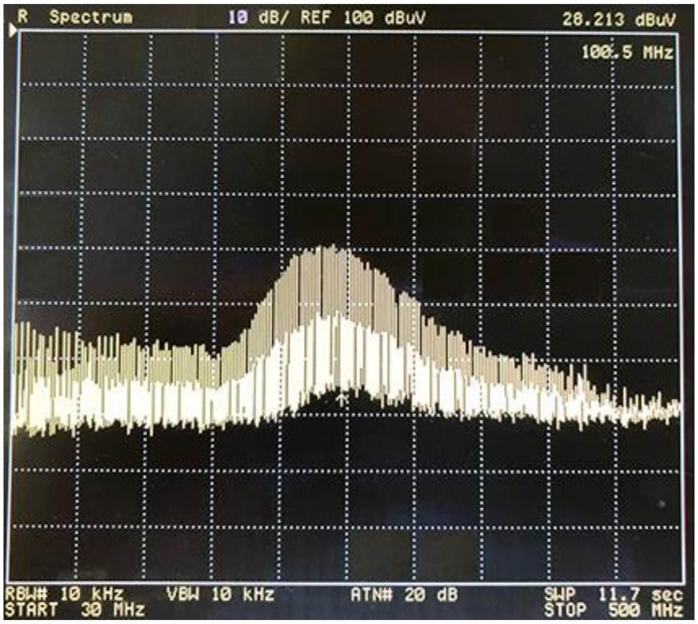

FIGURE 14: ELECTRIC FIELD AT THE TOP OF THE COIL, 30 MHZ TO 500 MHZ, WITH 0° ROTATION

The highest peak is 60 dB(µV) between 30 MHz and 300 MHz. Figure 15 shows the difference made by changing the polarity of the coil by 180° in a frequency range of 30 MHz to 500 MHz.

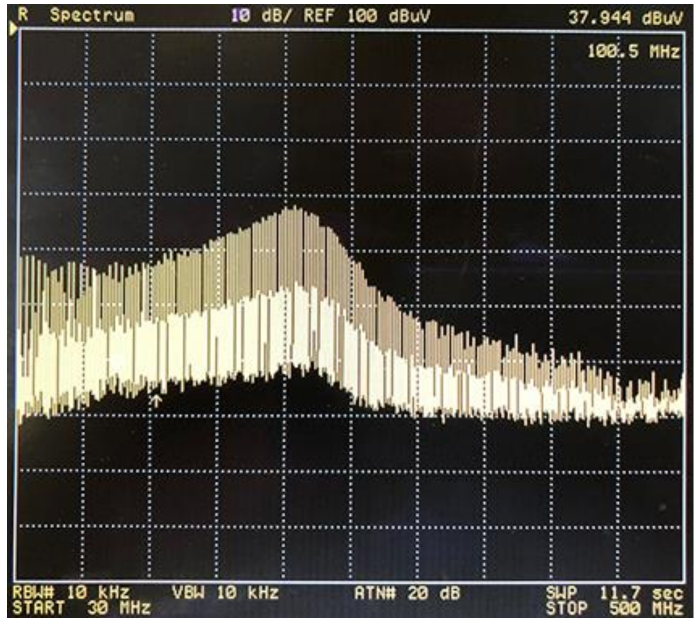

FIGURE 15: ELECTRIC FIELD AT THE TOP OF THE COIL, 30 MHZ TO 500 MHZ, WITH 180° ROTATION

Changing the polarity of the coil results in the electric field increasing by around 15 dB(µV) at the lower frequency range from 30 MHz and by around 10 dB(µV) at the frequency of switch node ringing.

Radiation from the SMPS

The SMPS converter emits electromagnetic noise through radiation of common mode currents from cables or antennas formed in loops in the design. Radiation is complex and depends on a number of factors. These factors include the common-mode current in the cables, the differential-mode noise at the SMPS input, the cable lengths, the loops in the power traces on the SMPS PCB, high dV/dt at the switch node, the coil polarity, and the coil size.

In the far field, an electromagnetic field consists of an E field which is perpendicular to the H field. The SMPS radiates electromagnetic noise over a wide frequency range, emitted by coil loops, power supply traces formed in loops on the PCB, and high dv/dt at the switch node.

A fast-switching MOSFET causes oscillations on the switch node in a frequency range of 40 MHz to 300 MHz because of parasitic effects from MOSFET and PCB traces, depending on the switching frequency of the SMPS. These oscillations create electromagnetic radiations, which may also depend on the coil polarity, over a broadband frequency range.

Radiation from SMPS depending on the power inductor

Changing the orientation of the coil changes the polarity of the H field of the coil as well, which is perpendicular to the E field on the switch node. Thus, the amplitude of the electromagnetic radiation in the frequency range of the oscillation at the switch node is also changed. The amplitude of the emitted peaks depends on the PCB design and the coil, but the peak value could vary between 10 and 20dBµV/m.

The same evaluation board is used to analyze the radiated emission depending on the coil orientation. Radiated emission from these test boards was measured using the CISPR 25 measurement setup. The battery is connected to the equipment under test via cables of 1.5 meters length in a shielded enclosure, located on a wooden table on a conductive metal plate.

Figure 16 shows a radiated emission test in a frequency range from 150 kHz to 30MHz. The coil terminal with the polarity mark is connected to the switch node of the DC-DC converter.

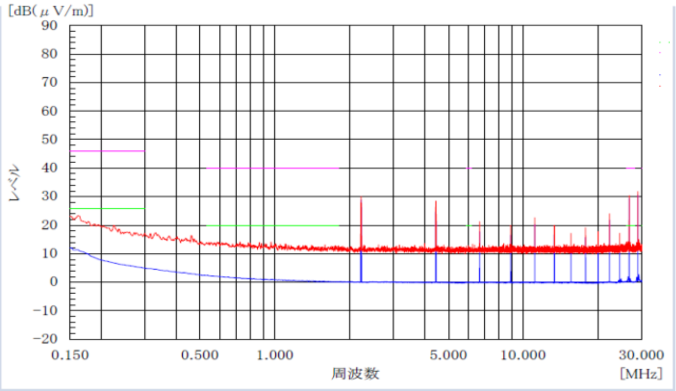

FIGURE 16: ELECTROMAGNETIC RADIATION FROM 150KHZ TO 30MHZ, COIL ROTATION IS 0°

This test result shows that the radiated electromagnetic noise of the DC-DC converter is below CISPR 25 level.

All test results are determined with a monopole antenna.

Next, the coil is rotated by 180° to analyze the radiation of electromagnetic noise according to coil orientation. Figure 17 shows the test result with the same board.

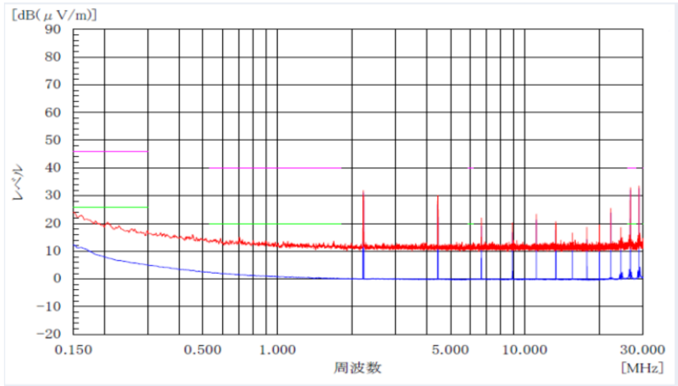

FIGURE 17: ELECTROMAGNETIC RADIATION FROM 150KHZ TO 30MHZ, COIL ROTATION IS 180°

In this frequency band, the difference between both tests is low. The switching frequency of 2.2MHz at the DC-DC converter and further harmonics are visible, radiated by input cables.

The DC-DC converter's radiated electromagnetic noise is below CISPR 25 level in this case. The amplitude of the radiated emission depends strongly on the input filter. Without an input filter, radiated emissions are much higher and much more influenced by the coil orientation.

Next, we are going to analyze the DC-DC converter's radiated electromagnetic noise in the communication band, based on the CISPR 25 standard, according to the coil orientation.

Figure 18 shows a radiated emission test in the communication band (30 MHz to 1GHz) with a coil orientation of 0°.

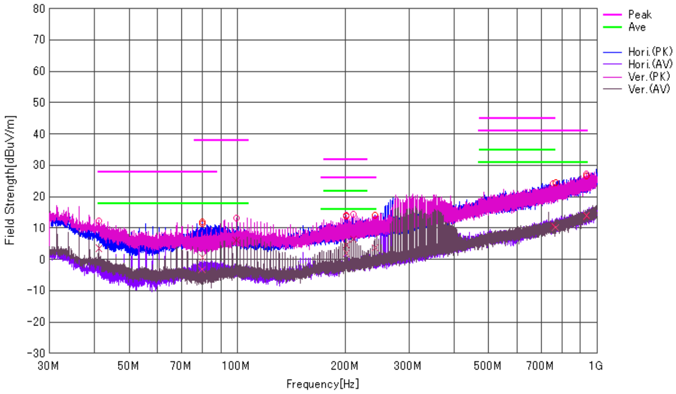

FIGURE 18: ELECTROMAGNETIC RADIATION IN COMMUNICATION BANDS, COIL ROTATION IS 0°

Again, this test result shows that the radiated electromagnetic noise of the DC-DC converter is below CISPR 25 level. A high noise level can be seen at the broadband frequency range of 70 to 100 MHz and 200 to 400 MHz, caused by oscillations in the PCB design.

Next, the coil is rotated by 180° to analyze the electromagnetic noise radiation according to the coil orientation. Figure 19 shows the test result with the same board.

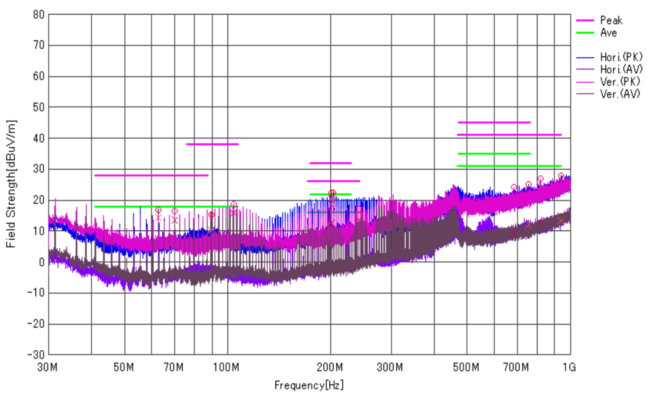

FIGURE 19: ELECTROMAGNETIC RADIATION IN COMMUNICATION BANDS, COIL ROTATION IS 180°

This test result shows a higher radiated noise compared to the test result from Figure 18, but the noise level is still below CISPR 25 level and the EMC test is passed.

Electromagnetic emission tests based on other standards, e.g. industrial standards such as EN55022, would yield different test results, because of different test setups. In contrast to the automotive standard CISPR25, the industrial standard EN55022 defines the measured electromagnetic radiation at the DUT from all sides, and not from the power supply cables.

Electromagnetic radiated noise depends strongly on, and is reduced by, an input filter placed at the input circuit of the DC-DC converter. All radiated emission tests were done with an input π-filter. However, changing the polarity of the input filter affects radiated emissions, too. Figure 20 shows the same evaluation board with the same setup and the coil of the input filter rotated by 180°.

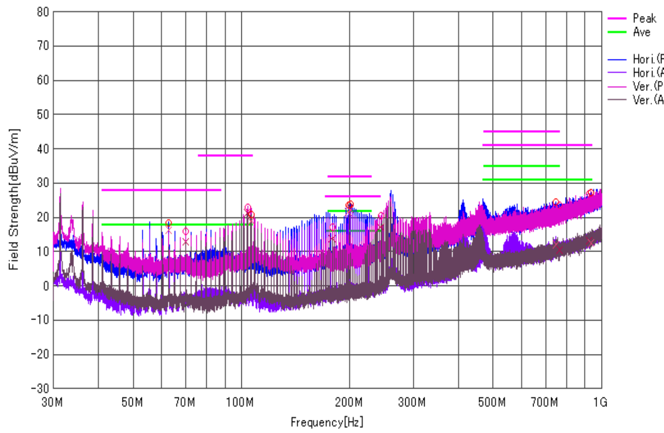

FIGURE 20: ELECTROMAGNETIC RADIATION IN COMMUNICATION BANDS, INPUT FILTER COIL ROTATION IS 180°

The radiated emission is increased by 10 dB(µV/m) between 30 and 40 MHz and by around 5 dB(µV/m) at 100 MHz, as well at 250 MHz.

Implementing power inductors in SMPS

In order to minimize the radiated emissions from electronic equipment and the coupling of magnetic flux by coils placed close to each other, the orientation of the coil needs to be considered during the schematic design of an SMPS as well as during its electronic manufacturing process.

For this reason, some coils have a defined winding direction. On some coils, one end of the wire is marked on the drum core by the manufacturer. The polarity of the shielded coil from TDK is indicated by a mark on the coil as shown in Figure 21.

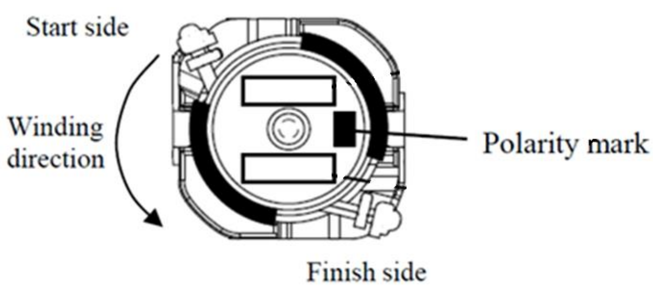

FIGURE 21: POLARITY MARK ON THE CLF-NI-D SERIES COIL FROM TDK

The current flow through coils can be defined in the SMPS by indicating the orientation of the inductor with the help of a polarity mark.

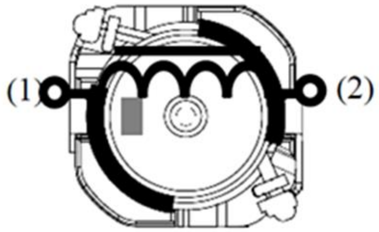

FIGURE 22: DEFINITION OF POLARITY MARK AND TERMINAL WIRING ON THE CLF-NI-D SERIES COIL FROM TDK

A polarity mark on the inductor, as shown in Figure 22, lets the user recognize the coil's wire ending which is connected to a defined terminal of the coil, as in this example from TDK's CLF-NI-D series.

With this mark, the current flow through the coil's wire can be defined, which in turn will determine the direction of the magnetic flux and magnetic field.

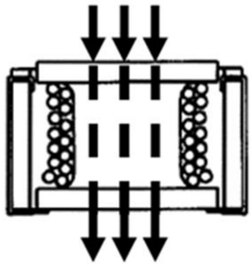

FIGURE 23: MAGNETIC FIELD DIRECTION IN THE CLF-NI-D SERIES COIL FROM TDK, FROM TOP TO BOTTOM

Figure 23 exemplifies the defined magnetic flux through the coil's drum core from top to bottom. This direction of magnetic flux is initiated by an electrical current flow from terminal no. 1 to terminal no. 2.

The direction of the magnetic flux also depends on the manufacturer of the coil and the coil's structure itself; it is not always the same as, or comparable to, the magnetic flux direction in other coils.

Conclusion

Radiated emission depends on the cables connected to the SMPS, on the PCB design, the applied power inductor, and the power inductor's orientation. Furthermore, the SMPS's radiated emissions can depend on the input filter as well.

The magnetic field and radiated emission tests illustrated in this application note show best results where the coil is connected as shown in Figure 24, with the polarity mark close to the switch node.

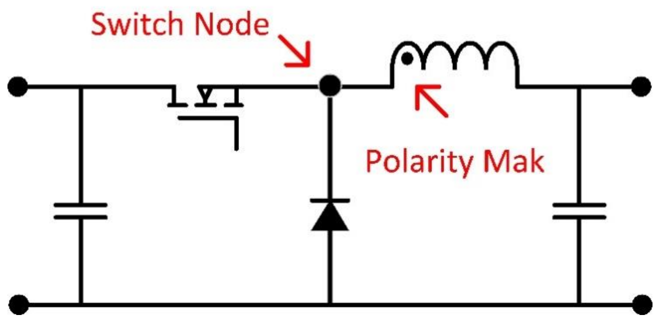

FIGURE 24: POWER STAGE OF DC-DC CONVERTER WITH DEFINED COIL ORIENTATION

Radiated emission can be reduced by reviewing the orientation of the inductor in the SMPS. The orientation of coils assembled on the PCB can be predefined by use of a polarity mark on the coil. It follows that the effects of magnetic coupling between coils placed close to each other can be minimized by this approach as well.

However, this effect needs to be tested in the target application by varying the orientation of the coil.

Naturally, selecting shielded coil types and small sizes improves the reduction of electromagnetic radiation from the SMPS as well.

By Stefan Klein, FAE, ATSC

Reference

(1) TDK, Selection Guide for Coils in Consideration of Leakage Flux
(2) TDK, Leakage Flux of Coils
(3) Takeshi Murase, Investigation of Buck Converter Radiated, Emission (150 kHz – 30 MHz) Measured, according to CISPR 25
(4) Y. Hoshino, SAGAMI ELEC Co. LTD, Tips for coil users

Notes

1) The information contained herein is subject to change without notice.

2) Before you use our Products, please contact our sales representative and verify the latest specifications :

3) Although ROHM is continuously working to improve product reliability and quality, semiconductors can break down and malfunction due to various factors.
Therefore, in order to prevent personal injury or fire arising from failure, please take safety measures such as complying with the derating characteristics, implementing redundant and fire prevention designs, and utilizing backups and fail-safe procedures. ROHM shall have no responsibility for any damages arising out of the use of our Poducts beyond the rating specified by ROHM.

4) Examples of application circuits, circuit constants and any other information contained herein are provided only to illustrate the standard usage and operations of the Products. The peripheral conditions must be taken into account when designing circuits for mass production.

5) The technical information specified herein is intended only to show the typical functions of and examples of application circuits for the Products. ROHM does not grant you, explicitly or implicitly, any license to use or exercise intellectual property or other rights held by ROHM or any other parties. ROHM shall have no responsibility whatsoever for any dispute arising out of the use of such technical information.

6) The Products specified in this document are not designed to be radiation tolerant.

7) For use of our Products in applications requiring a high degree of reliability (as exemplified below), please contact and consult with a ROHM representative : transportation equipment (i.e. cars, ships, trains), primary communication equipment, traffic lights, fire/crime prevention, safety equipment, medical systems, servers, solar cells, and power transmission systems.

8) Do not use our Products in applications requiring extremely high reliability, such as aerospace equipment, nuclear power control systems, and submarine repeaters.

9) ROHM shall have no responsibility for any damages or injury arising from non-compliance with the recommended usage conditions and specifications contained herein.

10) ROHM has used reasonable care to ensure the accuracy of the information contained in this document. However, ROHM does not warrants that such information is error-free, and ROHM shall have no responsibility for any damages arising from any inaccuracy or misprint of such information.

11) Please use the Products in accordance with any applicable environmental laws and regulations, such as the RoHS Directive. For more details, including RoHS compatibility, please contact a ROHM sales office. ROHM shall have no responsibility for any damages or losses resulting non-compliance with any applicable laws or regulations.

12) When providing our Products and technologies contained in this document to other countries, you must abide by the procedures and provisions stipulated in all applicable export laws and regulations, including without limitation the US Export Administration Regulations and the Foreign Exchange and Foreign Trade Act.

13) This document, in part or in whole, may not be reprinted or reproduced without prior consent of ROHM.

ROHM SEMICONDUCTOR

Thank you for your accessing to ROHM product informations.
More detail product informations and catalogs are available, please contact us.

ROHM Customer Support System

http://www.rohm.com/contact/