Common Mode Chokes Basics and Applications

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Introduction

Multiple standards have been developed by regulatory agencies and organizations such as the FCC, CE, ISO, and others to set the rules and regulations needed to establish the electromagnetic compatibility (EMC) requirements of all electrical and electronic systems in their respective jurisdictions.

EMC refers to the ability of the electrical and electronic systems to operate correctly in the electromagnetic environment by limiting the generation, transmission, and reception of undesired signals through electromagnetic interference (EMI) between the different systems or within the system components.

Product designers are required to keep the radiated electromagnetic emissions under the limits set by the regulatory agencies, prior to introducing these products to the market. Therefore, EMC requirements are assessed and monitored carefully while designing the product.

Electromagnatic Interference (EMI)

Electromagnetic interference (EMI) corresponds to the unwanted electromagnetic disturbance or noise signal that is introduced in electronic systems by external or internal sources. These sources can be other systems in the vicinity, such as radio transmitters, power grid systems, cell phones, switching power supplies, electrical motors, or even natural sources such as lighting and solar flares.

All EMI sources transmit the noise energy to electronic systems through one of the following mechanisms: radiation (which is the most common), electrostatic discharge (ESD), or physical conduction. EMI sources can affect the integrity of electrical signals in the electronic systems in the vicinity, leading to faulty operation conditions, degraded performance, and even permanent damage to the equipment. Therefore, attention must be given to the EMC during the design phase to protect nearby systems and to meet the requirements mandated by the regulatory agencies.

What are Common Mode Chokes?

Common mode chokes are used in both power and signaling circuits. Data lines in electronic communications systems usually exist as pairs where they transmit signals of equal amplitude but opposite polarity. These lines are known as differential signals or pairs, such that the transmitted signal is sensed at the receiver by taking the voltage difference between the two lines.

Differential pairs are susceptible to two main types of noise: differential mode noise and common mode noise. Both types of noise are coupled to the system through one of the three mechanisms discussed earlier. The difference lies in how and where the noise is originating. Differential noise couples only to one of the two lines before propagating in the system, while common mode noise couples to the differential pair and propagates through both lines in the same direction simultaneously. To eliminate or reduce the effect of both types of noise, designers usually incorporate different techniques throughout the production stages. Some of these techniques involve external metal shielding; optimized routing for proximity; and component layout and circuit-level protection by utilizing passive filters.

It is common in the design process to utilize a combination of various techniques to mitigate the effects of EMI and to produce a robust product that satisfies the regulatory requirements. Implementing circuit-level protection involves different filter topologies and components, which are employed to reduce both common and differential noise. One of the discrete components that has been designed specifically to combat common noise is the common mode choke (CMC).

A common mode choke is a passive electromagnetic device that permits the passage of the desired electrical signals through data or power lines while filtering out the unwanted high-frequency noise signal from external sources or other circuits of the system.

How it Works

When common noise is introduced in the differential pair, as it propagates through the common mode choke, it induces a magnetic flux in both windings of the CMC. The windings are physically structured such that the magnetic flux induced by the noise on one line combines with the magnetic flux generated on the other line, creating a rotating magnetic field within the CMC core. At this instant, the CMC is essentially acting as an inductor with an impedance that is proportional to the impedance at the noise frequency. This mode of operation, referred to as "Common Mode," allows lower frequencies to pass while impeding the high-frequency noise.

Conversely, if the current of the differential signal being sent through the signal pair flows in opposite directions, each line induces a magnetic flux that is equal to the other line in magnitude but has the opposite polarity. This causes the two induced magnetic fluxes to cancel each other out, allowing the differential signal to pass with minimal attenuation.

Theoretically, it is impossible to drive the CMC core into saturation by the effect of the differential signal. Therefore, manufacturers specify their current rating through the temperature rise due to copper and core losses.

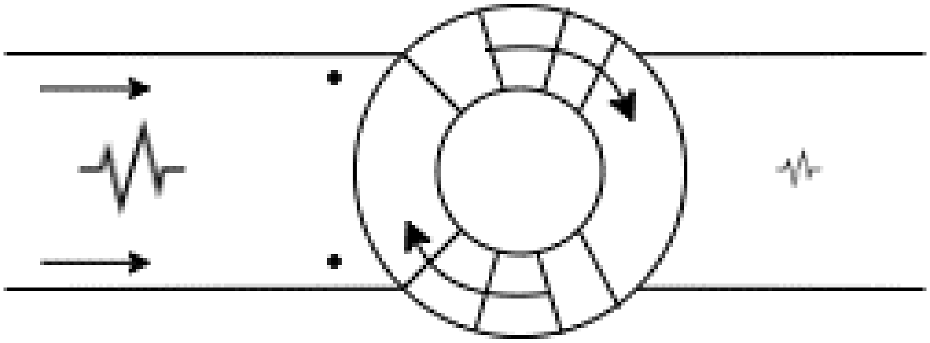


Fig 1. Magnetic fluxes combining due to common signal

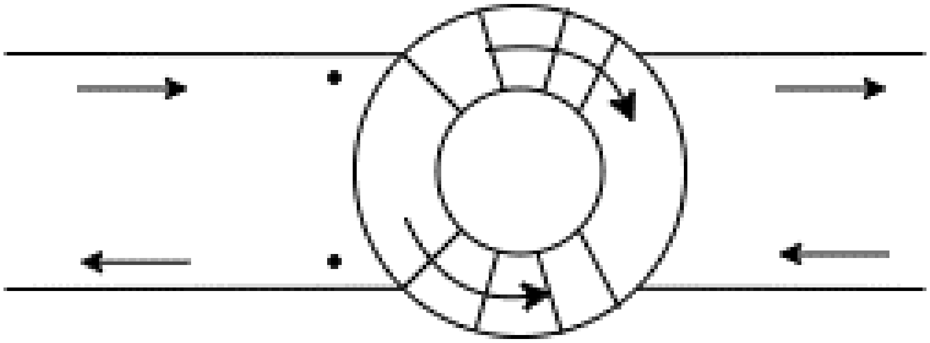


Fig 2. Magnetic flux cancelation due to differential signal

Types of CMCs

There are two interchangeable ways to classify CMCs: First, by the type of line being filtered—leading to power or signal line classification. The other way is by the frequency range of the application where they are characterized as radio frequency (RF) chokes or audio frequency (AF) chokes.

AF CMCs are used to suppress noise at the audio frequency range (up to 30KHz). Example applications where power CMCs are used include switch-mode power supplies (SMPS), AC/DC Rectifiers, Electrical Ballasts, Power Inverters, and Variable Frequency Drives (VFDs).

For applications implementing differential signal lines or RF chokes, the noise frequency is much higher (Above 30KHz). Signal CMCs are commonly used in USB, HDMI, LVDS, CAN bus, and Ethernet applications.

The difference in the electrical specs between the two is mainly derived from the type of core material used. AF CMCs are more suitable for power line applications as they utilize solid iron cores with high saturation and current ratings compared to RF CMCs, which use powdered ferromagnetic core materials rated for lower current applications.

CMC Circuit Model and Equations Derivations

The impedance frequency characteristic is one of the important parameters to consider when choosing a CMC. As described earlier, when common mode signals are passing through the differential line, the CMC will act as a filter that will attenuate those common signals based on their frequency. The higher the impedance at those frequencies, the more attenuation that those signals will experience. The general rule of thumb is to choose CMCs with the highest impedance at the expected noise frequencies.

To observe the impedance vs frequency behavior of CMC in common mode, a low-current high frequency model is used for each inductor. The common mode signals see both inductors in parallel as follows:

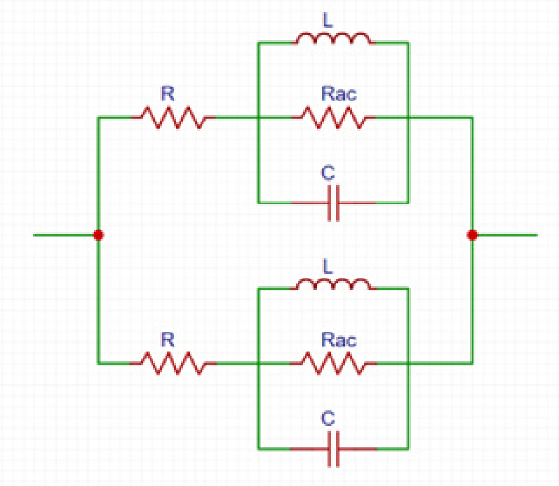


Fig 3. CMCs model in common mode

Rac: Represent AC losses
L: The inductance of the winding
C: Interwinding capacitance
R: Resistance of the winding
Both windings are assumed to be identical with no flux leakage to make calculations simpler.
The equivalent impedance of this model is calculated as follows:

$$Z_{eq} = [\,R + (Z_L//R_{ac}//Z_C\,)\,]\,//\,[\,R + (Z_L//R_{ac}//Z_C\,)\,]$$

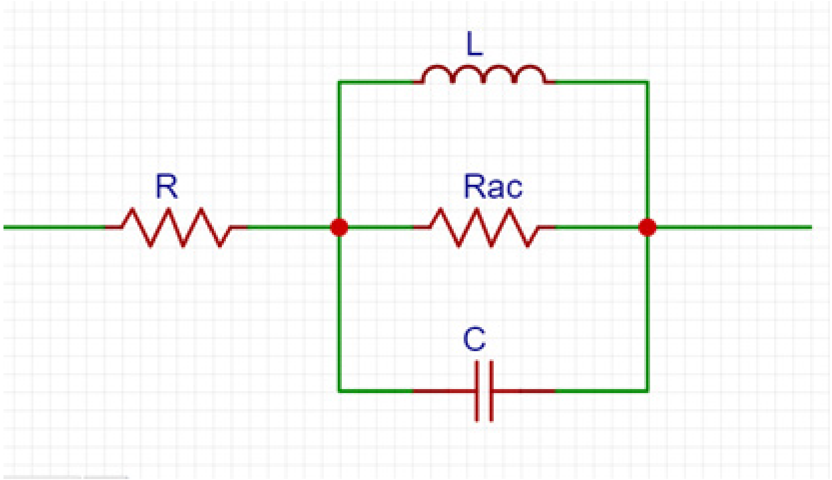
Where:

$$Z_L = j\omega L$$
$$Z_C = \frac{1}{j\omega C}$$

Since both windings are equal and in parallel, the equivalent impedance becomes:

$$Z_{eq} = [\,R + (Z_L // R_{ac} // Z_C\,)\,]/2$$

The circuit is simplified to the following:



From Parallel RLC circuit:

$$Z_{eq} = \frac{\left[R + \left(\frac{1}{\left(\frac{1}{Rac}\right) + j\left(\omega C - \frac{1}{\omega L}\right)}\right)\right]}{2}$$

Then, by taking the magnitude:

$$|Z_{eq}| = \frac{R}{2} + \frac{Rac}{\sqrt{4 + 2\,Rac\,(\omega C - \frac{1}{\omega L})^2}}$$

Equation 1: impedance magnitude as a function of frequency

Abracon ACMS-Q3225E-201-T has been used to evaluate the precision of this model. Both differential and common mode impedances have been measured against frequencies up to 1 GHz, as shown in figure 4 below. In addition, the equivalent circuit parameters have been extracted by using an E4991B Keysight Impedance analyzer.

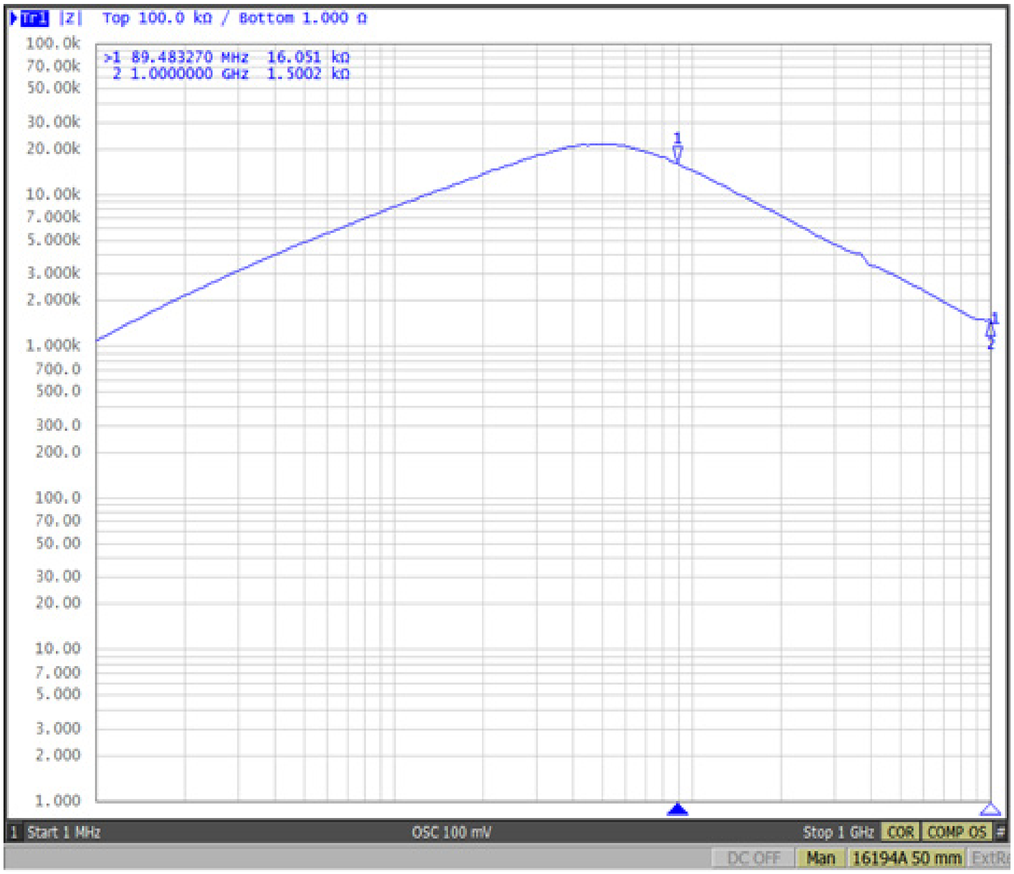


Figure 4: Common and differential impedance of ACMS-Q3225E-201-T

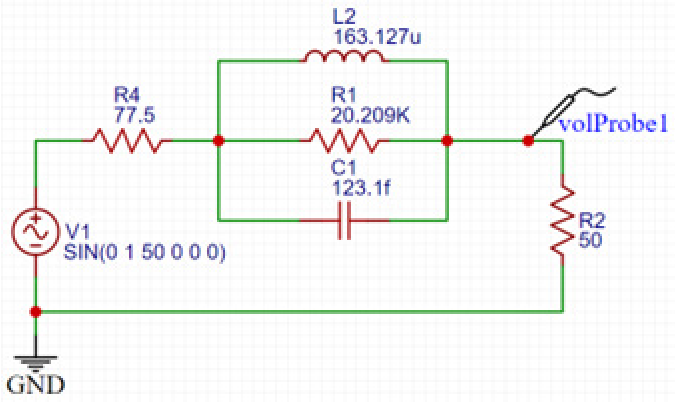


Figure 5: Equivalent model parameters of ACMS-Q3225E-201-T

From figure 4 above, it can be seen that the impedance starts with 1K ohm at 1MHz and keeps increasing until it peaks at 17MHz, where it starts to resonate. Then, it starts declining with increasing frequency as the capacitive impedance begins to dominate.

By using equation 1 and the equivalent parameters in figure 5, the common mode impedance of ACMS-Q3225E-201-T is graphed against frequency on a logrothmic scale as shown in figure 6 below.

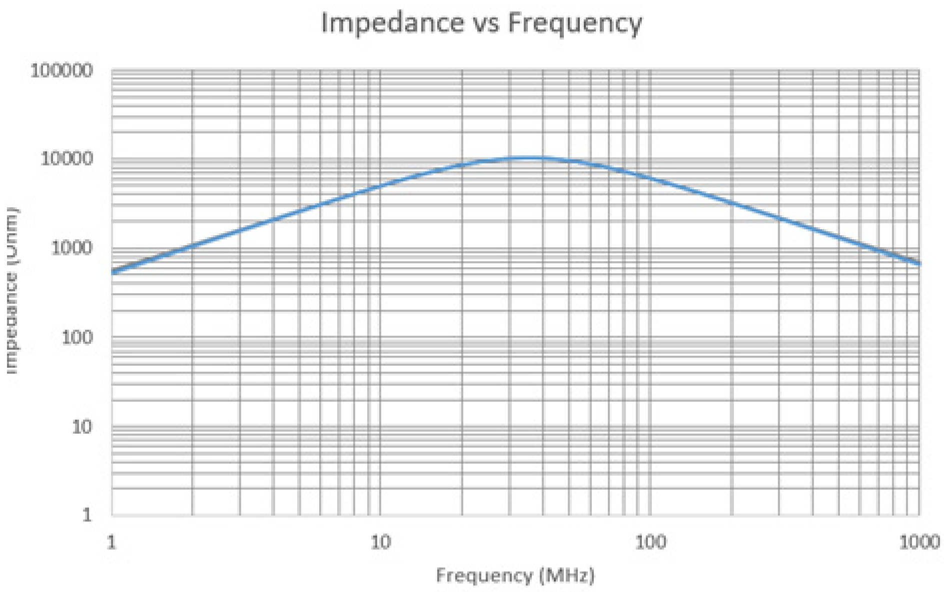


Figure 6: Impedance vs frequency graph of ACMS-Q3225E-201-T

By comparing figures 6 and 4, it can be observed how closely the measured impedance matches the plotted graph that's based on the equivalent model shown in figure 5. This is specifically helpful during the design phase by allowing the designer to model CMCs in a simulation tool to observe their in-circuit effect on common mode noise.

How to Choose CMC?

There are few constraints to consider when choosing a CMC for proper operation in each application:

Required attenuation:

The most common way of measuring attenuation of the CMCs is to measure its impedance. However, another method is to measure the inductance, and it is frequently used to characterize signal line CMC's. Regardless of the method used, the general rule is to choose the CMC with the highest attenuation which typically means a larger component size. Larger components can cost more and may be harder to fit in dense PCB designs.

Current requirement:

As noted earlier, since the core cannot saturate, the current rating of the CMC is based on the temperature rise. Therefore, it is necessary to choose a CMC with a rating well above the maximum expected differential current.

Choosing a CMC for a signal line application must be done such that the integrity and quality of the signal is not compromised. Different communication standards like Ethernet, CAN, CANFD, and others require picking CMCs with impedance characteristics that are compatible with the transmission line. Abracon manufacturers CMCs that are specifically designed to be integrated with the mentioned standards.

Other specs to consider include adequate frequency range, low DC resistance to limit the copper losses, higher voltage ratings to avoid voltage breakdowns, and low interwinding capacitance.

CMCs in Automotive Applications

As the auto industry's boom continues, the adoption of electronic devices in automobiles has grown rapidly. Thanks to this trend, vehicles can now be equipped with a variety of features, such as infotainment systems, ADAS (advanced driver-assistance systems), navigation systems, OBD (on-board diagnostics), and others. CAN bus (Controlled Area Network) is one of the communication standards that allows all these features to function in unison. It uses two-wire differential signaling to send and receive data from the different devices in the network. While the nodes of the bus can be near other EMI sources in the vehicle, the design of a robust CAN bus that can withstand all incoming noise is integral to delivering a reliable and safe vehicle. In addition to other filtering techniques, CMCs are one of the devices that are used to combat noise in a CAN bus.

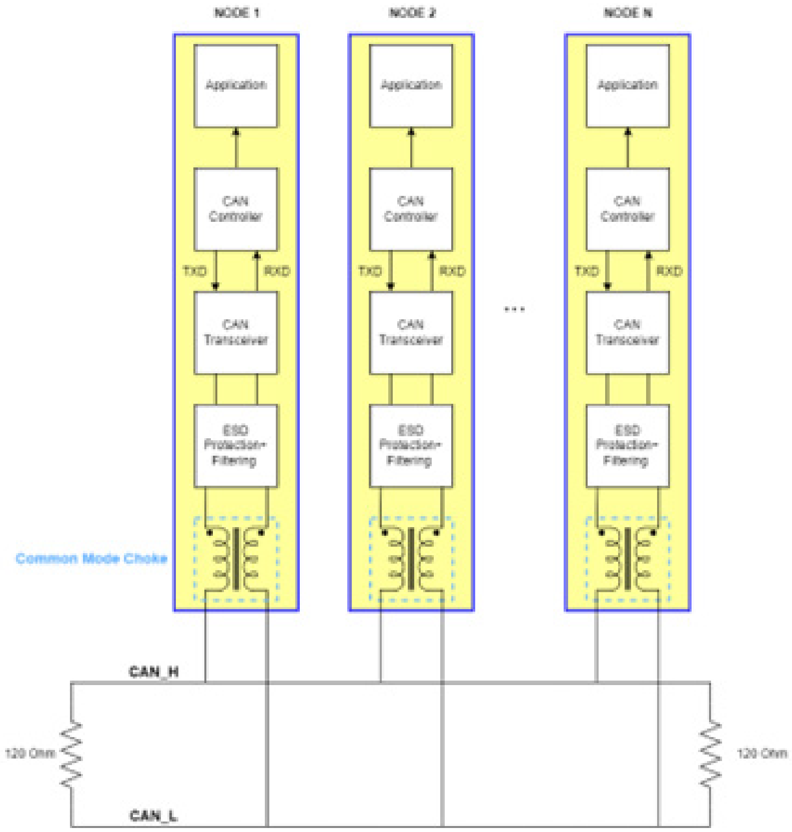


Figure 7: CAN bus Nodes connections and CMCs locations

As shown in figure 7 above, CMCs can be used as an interface between the CAN transceiver and the bus high and low lines to prevent common mode noise from coupling to the transceivers. For example, CMCs are used in conjunction with other devices such as bypass capacitors and TVS diodes to provide protection to the transceiver.

High voltage transients generated unexpectedly by the CMC are one of the potential issues that require extra caution when using a CMC. As the transceiver is shifting the lines from recessive to dominant mode or vice versa, the slight period where both lines are shorted to a DC voltage can cause unwanted voltage spikes that may damage the transceiver if not handled correctly. The transient can be reduced by adding ESD protection devices such as TVS (Transient Voltage Suppressor) or MOV (Metal-oxide varistors).

Conclusion

To summarize, CMCs are unique, specialty devices that are used specifically to reduce common mode noise while allowing differential signals in communications systems or power lines to pass through with little to no attenuation. They solve the problem of having to use two separate inductors for each line, which would affect the integrity of the desired electrical signal. Moreover, they are necessary to prevent faulty operating conditions, malfunctioning and performance degradation, damage sensitive electronic components, and meet the mandated regulatory specifications (IEEE, CISPR, EN, ISO, etc.).

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