MANAGING ELECTROMAGNETIC INTERFERENCE IN LARGE INSTRUMENTATION SYSTEMS*

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Abstract

Implementing high-quality measurement systems in large test environments presents a number of unique challenges. And, these challenges are made even more interesting where new instrumentation systems are being implemented in existing legacy environments where there is little opportunity to modify the infrastructure. Often, Electromagnetic Interference (EMI) is encountered. This interference may be simply an annoyance when sufficiently low that data integrity is not severely compromised, but in many cases, perhaps most, EMI is so severe as to totally obscure the signals of interest. Various sources of EMI and common points of entry of are reviewed. Means of mitigation of EMI in the design and implementation of instrumentation systems in legacy environments are presented. Common sources of EMI potentially introduced by the instrumentation systems themselves are examined, and means of design to mitigate such self-induced interference are examined. Real-life examples are provided to demonstrate the EMI issues, and the effect of mitigation. It's all about the current – pretty much!

EMC vs EMI

Virtually everyone involved in instrumentation systems has encountered electronic noise that corrupts data acquisition. Two terms used in instrumentation venues in discussion of electromagnetic effects are Electromagnetic Compatibility ("EMC") and Electromagnetic Interference ("EMI"). Often it is found that these two terms are used somewhat interchangeably. This however is incorrect interpretation of the terms.

EMC is a goal to be achieved. EMI is a corrupting signal compromising competent collection of data signals. Very simply, the goal of EMC is to minimize EMI.

Specifically, the goal of EMC is to "minimize" EMI, but not to totally eliminate the EMI signals. Interfering signals need only be reduced to the level that allows competent collection of the signals of interest. Although it may be feasible to further reduce EMI, there is little to be gained in terms of the data acquisition, and there may be significant increases in cost and time.

EMC is most effectively managed in the initial design of a facility. At this point, such critical elements as grounding structures, placement of high-energy sources, instrumentation placement, high-energy cable parameters, high-energy cable routing, signal-cable parameters, signal-cable routing, conduit systems for carrying high-energy and signal cables, and virtually all other characteristics of the facility may be addressed to attempt to assure that interference is minimized.

However, typically the facility infrastructure is designed to support the mission, and the instrumentation systems simply must live in this environment. And in many cases, perhaps most, instrumentation systems must be implemented in facilities and systems that have been in place for a very long time, e.g., legacy systems.

STANDARDS AND REFERENCES

There are numerous EMC standards. A number of IEEE publications address the EMC topic, and one of the more common references is MIL-STD-461 [1]. In general, two specific types of emissions are considered: Radiated Emissions ("RE") and Conducted Emissions ("CE"). Similarly, two specific types of susceptibility are considered: Radiated Susceptibility ("RS") and Conducted Susceptibility ("CS").

Although standards are necessary and valuable, these simply define emissions allowable from a source, and the required tolerance to emissions of systems exposed to the allowed emissions. Standards tell you what you must do, but do not give you any guidance as to how to do it.

There are also numerous "How To" references providing insight into both control of emissions and minimizing EMI. One of the industry standards is *Noise Reduction Techniques in Electronic Systems* by Ott [2]. However, in many cases, these references are highly theoretical and very general, and it is often found that it is quite difficult to apply the guidance in "your" systems. And, often the guidance provided is more easily implemented in new designs, and more difficult in legacy systems. For example, just how does one implement a "single-point ground" and avoid "ground loops" in a new cable plant installation in a facility where cable plants are as much as a hundred meters long, and perhaps even much longer, and where all the high-energy cables and other potential noise sources are permanently in place?

CLASSIC EMC DESIGN PROCESS

There is no standardized process in applying EMC principles to minimize EMI. Every situation is unique, and must be examined independently based on the specific system elements and the operational requirements. However, the general design approach to assure EMC reviewed in many references is typically the control of the emissions at the source.

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Several classic EMI mitigation approaches that are commonly suggested are listed in Table 1.

Table 1: Classic EMI Migration Approaches

At the Source	At the Receiver
Shielding	Shielding
Grounding	Grounding
Shielded Source Cables	Shielded Signal Cables
Shielded Signal Cables	Shielded Source Cables
Balanced Source Signals	Balanced Data Signals
Filtering	Filtering
	Separate Equipment Ground
	Cable Routing
	"Single-Point Ground"
	"Eliminate Ground Loops"
	Etc.

In general, all of these approaches listed in Table 1 are simply common sense. However, two of the items are particularly interesting: "Single Point Ground" and "Eliminate Ground Loops." Here again it is simple to direct that one should utilize a single-point ground, and should assure that all ground loops are eliminated, but actually following this advice is typically difficult if not impossible.

For example, how does one effect a single-point ground in a facility that is a kilometer or more in extent, and where the majority of the grounding in the facility is predetermined? And, just what is a ground loop? Why is it a problem? And even if a ground loop is discovered, can it be even be effectively broken, and if so, can it be broken without compromise of facility operations, or more specifically, broken without compromise of safety? So again, the advice may be sound, but not particularly useful since it may be impossible to implement.

UNDERSTANDING EMI

The very first task in EMC design and EMI mitigation is the understanding of EMI. What must be recognized is that one person's signal is another person's EMI.

For example, the signal of a nearby high-power radio transmitter may interfere with your television reception or the operation of other wireless devices. The high-power RF is of course the intended signal of the transmitter, but its effect on your systems is EMI. In this example, one would have no control whatsoever at the source.

Similarly, in big-physics systems, such as accelerator facilities, the overall design of the facility is primarily to support the physics. For example, the high-current, high-energy signals applied to bending magnets and kickers are signals necessary to competently operate the system. Any related signals that adversely affect data acquisition in the instrumentation are EMI. And here too, it may not be feasible to change the facility infrastructure at the source to reduce EMI at the instrumentation since that is determined by the needs of the physics.

In this paper, the author presents a somewhat non-traditional definition of EMI. In general, EMI is most often defined as something that is done to your system from various external sources. However, in many cases of EMI contamination of signals, the actual root cause of the EMI is internal to the instrumentation system itself. And, very often these are obscure, easily overlooked, and if not recognized, can be very difficult to control.

The author's definition of EMI in an instrumentation environment is simply:

> **EMI is *any* electrical signal adversely affecting data quality whether from external or internal sources**

This statement may seem obvious and innocent enough, but as reviewed in the real-life examples below, some of what is identified as EMI in this paper is not all that obvious. And some may argue that such electrical effects are not actually EMI, even though the measurements are compromised by these unwanted electrical signals. However, based on this definition, any interfering electrical signal regardless of its source, or its nature, is defined by the author as EMI.

The most important aspect of control of EMI is developing a very accurate understanding of why EMI occurs. If the actual root cause of an EMI contamination is due to sources internal to the actual instrumentation system, but this is unrecognized, and one proceeds to try to locate and mitigate the EMI by examining and modifying external elements, the task will be exceedingly laborious, and very likely much less than successful.

There are no cookbook methods to EMI mitigation, and there is no one-size-fits-all configuration to assure adequate EMC in a complex system environment. Accordingly, all upfront EMC considerations in new facilities, and all EMI mitigation needed in legacy facilities, must be engineered for each specific case.

JUST WHAT IS EMI

To this point, the term "EMI" has been repeatedly referenced, but no actual sources have been identified. In general, EMI is a broad catchall term used whenever some electrical noise is encountered. So, just what are some the common sources of EMI?

One very common source of EMI is the result of noise on the AC power MAINS coupling into the instrumentation systems. Often this noise is from indeterminate sources. It is just there!

Other common sources of EMI are various infrastructure equipment within the facility. Some examples of such sources are high-energy power supplies, variable-speed motor drives, contactors, high-intensity discharge lighting, solid-state ballasts, other MAINS

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devices, and countless other equipment common in almost every facility.

But not all sources of EMI are external. Some EMI we do to ourselves internal to our instrumentation systems. Some typical examples of internal EMI sources are switch-mode power supplies, motor-drive systems driving various motive sensors such as wire scanners, and even digital electronics such as high-speed microcontrollers.

Almost any internal element can be a source of EMI, even very low-frequency sources, even DC sources, and even the signals themselves. Often these internal EMI sources are the most elusive to isolate, but can be straightforward to mitigate since one typically has reasonable control of the actual instrumentation system.

There are of course environmental sources of EMI. A typical example is lightning. Although this is a low duty-cycle transient, it is still quite significant since the instrumentation must at least survive even nearby strikes. And often this EMI occurs at the most inopportune time causing loss of data.

Also, less obvious environmental sources of EMI are earth currents, although technically not all are truly environmental. These can be due to true geological effects such as geopotentials between physical positions, such as between one point in a facility and another point in the facility far removed from the first. But more often these are related to such things as currents due to AC MAINS power distribution, currents induced in the ground structure of RF sources such as radio and television transmitters, as well as other wireless devices.

These are loosely termed environment since they live in the earth itself. And, due to the extremely low impedance typical of these sources, it is virtually impossible to eliminate, or even reduce, these EMI sources by shunting around the source, for example by installing massive ground buses and grounding straps. Further, the installation of such grounding features can actually inadvertently create ground loops. So, in some cases, the more one does to solve an EMI problem, the worse it gets.

Finally, one absolute boundary condition of EMI is first-principle noise, specifically thermal noise and shot noise. These noise sources are not typically viewed as EMI sources, but these fit very accurately in the EMI definition above. And, this EMI cannot be eliminated! However, these noise sources are a function of measurement bandwidth, and therefore only the bandwidth necessary to competently capture the data of interest should be utilized in order to minimize this EMI. And such bandwidth limiting is always a good practice in all instrumentation applications.

THE INSTRUMENTATION ENVIRONMENT

The actual instrumentation environment in which one is constrained to work directly affects the application EMC and EMI-mitigating principles.

As noted above, EMC is most effectively managed in new, purpose-built systems being designed and built from the ground up. Here the instrumentation team has some opportunity to affect the facility design to try to assure some acceptable degree of EMC. However, in many facilities, if not most, the actual purpose of the facility drives the infrastructure design. For example, in big-physics systems such as accelerators, the physics almost exclusively drives the design of the structures.

Legacy systems present a much greater challenge since virtually all EMI issues must be solved without any substantial changes to the infrastructure.

GROUNDING

Grounding is often a critical parameter in instrumentation systems, and is almost always the most controversial. What to ground, how, and where, is typically the source of lively debate.

Facility Grounding

However, typically very much of the grounding structure in a facility is predetermined and may not be altered. Safety grounding of all MAINS operated equipment may never be removed. Metal cable trays, metal conduits, counterpoise, and even the system being instrumented, such as an accelerator, are all grounded. Typically this facility grounding may not be altered in any substantial manner.

Sensor Grounding

Very many of the sensors utilized also are grounded. Specifically, the sensor output signal is presented single ended with respect to the conductive body. Two typical such sensors are shown in Fig. 1.

Figure 1: Typical Grounded Sensors.

The first sensor in Fig. 1 is a Bergoz Beam Current Monitor [3], and second is a T&M Research Products Current-Viewing Resistor ("CVR") [4]. Both of these sensors are configured with a single-ended output connector tied to the conductive body, and the conductive body is also part of the sensor active element. Therefore, the grounding at the point of measurement is very often predetermined with sensors such as these.

Instrumentation Grounding

Grounding is also typically predetermined at the instrumentation. All MAINS-operated equipment is grounded to assure electrical safety. Although it is feasible to utilize fiber optics, high-isolation power supplies, and other means to provide isolation, these are

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often costly, complex, and can introduce reliability concerns, e.g., battery-operated equipment.

Instrumentation-Cable Grounding

It may seem that the instrumentation engineer has total discretion in grounding of instrumentation cabling. The basic question that then arises is just how to ground cabling, and to what?

Also, the instrumentation cabling is typically routed through metal conduits, along metallic cable trays, and even along walls and flooring that have embedded metallic structural members that are grounded. The cable routing itself results in capacitive coupling from the cable to ground. This effectively creates the dreaded ground loop inviting EMI coupling at higher frequencies.

SIMPLE EMI REAL-LIFE EXAMPLES

It is most useful to actually demonstrate several examples of EMI and to show specifically how this EMI finds its way into data systems. However, the next EMI examples may not seem appropriate for a tutorial on EMI, but hopefully after reviewing the cases, the reader will be convinced that these are indeed examples of EMI. It's all about the current – pretty much.

The author likes to use the CVR in real-life examples demonstrating often-unrecognized effects of EMI. The CVR is perhaps the simplest of sensors – it is simply a resistor, nothing more. And it has been suggested that "the CVR is so simple that one simply cannot do it wrong!"

Consider that measurement of the RF currents from 1 kHz to several megahertz is to be made on a magnet power supply using preinstalled 1 mOhm CVR devices as in Fig. 1. It is therefore important to know the frequency response of the sensor. This may be easily collected using a network analyzer. Figure 2 is a typical frequency-response measurement configuration.[1]

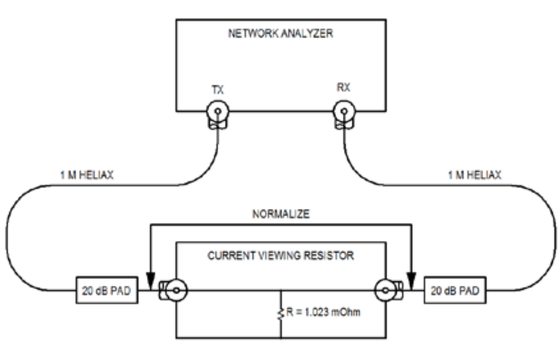

Figure 2: CVR Frequency Response Measurement.

One would expect the response of the CVR to be flat from DC to some break frequency, and then drop into the network analyzer noise floor. However, this is not the case. Figure 3 is the response actually observed.

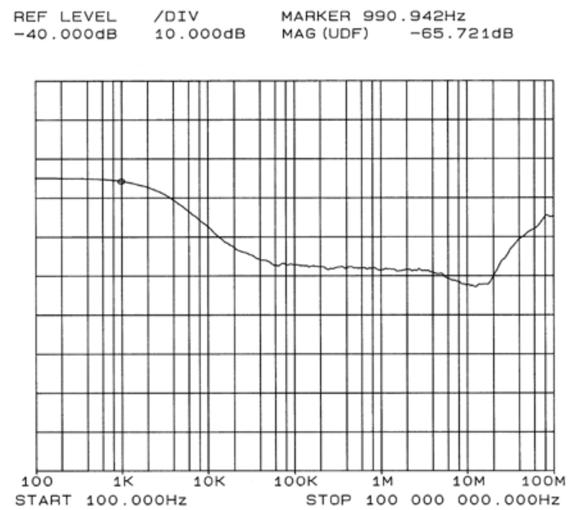

Figure 3: Apparent 1 mΩ CVR Frequency Response.

The response of Fig. 3 shows a quite serious anomalous response below nominally 100 kHz, and this extends to true DC. The DC resistance of this CVR is 1.023 mOhms. At 1 kHz and below, the apparent CVR impedance is 12.9 mOhms. Therefore, there is a 22 dB measurement error at 1 kHz, and all the way down to DC.

One might conclude from this response that the CVR is in some way defective, or perhaps even that the network analyzer is defective. However, this anomalous response is due to EMI, and EMI introduced by the measurement itself. But this EMI is not what is typically recognized as EMI, and therefore this EMI effect is easily overlooked.

If this CVR were used to record the frequency characteristics of the current of the magnet power supply, and this EMI contribution were not known, and the response of Fig. 3 were used as the "calibrated" response characteristic of the sensor, the results would be seriously in error at 1 kHz, specifically 22 dB in error, and this error would extend to DC. And since the CVR is so simple that one simply cannot use it wrong, it would prove very difficult to determine why the magnet power supply "appears" to be behaving in a strange manner.

This anomalous response is due to shield currents in the signal cables. To demonstrate this, again with a real-life example, the author removed the center pin and insulator from an SMA barrel connector, soldered an RF block into the connector to provide RF isolation between the two ports, and connected this in the test configuration of Fig. 2 as the test article in place of the CVR. This is shown in Fig. 4.

This test article now allows the signal-cable shields to be connected at the point of measurement, but with the center conductors open, and shielded from each other.

In this measurement, one expects the response to simply be the network analyzer noise floor since the center conductors of both the source and receiver cables are open and well shielded from each other at the point of

1. The 20 dB pads are utilized to assure that all signal cables are properly terminated since the test article presents a severe mismatch. With these pads included, the impedance seen by the signal cables is effectively the proper terminating impedance regardless of the characteristics of the test article.

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measurement. Figure 5 shows the actual response collected.

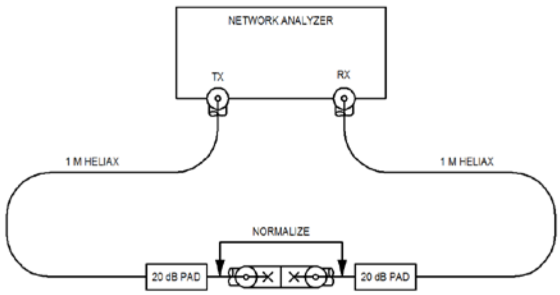

Figure 4: Cable-Current Artifact Measurement.

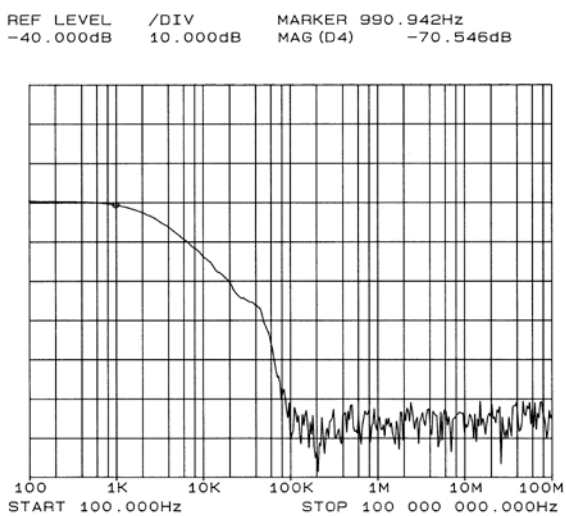

Figure 5: EMI Measurement Artifact.

The response of Fig. 5 looks suspiciously similar to that of the CVR in Fig. 3. And indeed this is an EMI signal. And this is the root cause of the anomalous response seen in Fig. 3.

This response is caused by shield currents. Current flows from the source, to the test article, through the terminating pad, and then returns on the shields of both the source and receiver cables. At low frequencies, the transfer impedance of the cable approaches simply the cable resistance. Therefore, a potential is developed on the "outside" of the receiver cable, and this potential is communicated to the center conductor through the terminating pad. The result is a potential, i.e., EMI, introduced into the receiver as witnessed by Fig. 5.

Oddly, the root cause of this form of EMI is the signal itself. This is not typically what is envisioned when the term EMI is used. But, based on the definition above, it is a corrupting electrical signal, and is therefore EMI by that definition. And, if one is not familiar with this type of EMI, measurement results as shown in Fig. 3 are very difficult to reconcile, and the EMI even more difficult to mitigate since the root cause is illusive.

Since the network analyzer connector grounds are electrically connected at the network analyzer, and the feed-line shields are also connected together at the test article, a "ground loop" is created. However, in this example, there is no external magnetic field penetrating the loop, so one would expect no worrisome shield currents. So, the shield currents would go undetected. And, even if one recognized this ground loop, it cannot be easily broken since the RF integrity of the measurement must be maintained. Also, if this ground loop were discovered, and the loop area were reduced by keeping the signal cables very near the network analyzer, there would be no change in the anomalous response, and it would be concluded that this ground loop is not the source of the EMI. And again the shield currents would go undetected.

If the shield currents can be reduced, the quality of the measurement may be improved very substantially. The frequency-response measurement of Fig. 3 was repeated, but with the addition of a simple common-mode isolator in the receiver signal line (the common-mode isolator is reviewed in detail below). The resulting response is shown in Fig. 6.

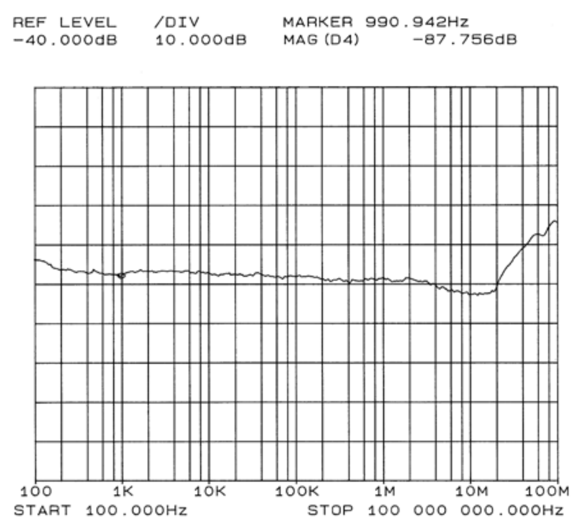

Figure 6: Improved 1 mΩ CVR Frequency Response.

At 1 kHz, the CVR impedance is now seen to be 1.024 mOhms, which agrees very well with the DC resistance measurement. The specific common-mode isolator utilized in the measurement of Fig. 6 was designed specifically for this example to provide just sufficient reduction of the EMI to allow accurate measurements down to just below the specified 1 kHz measurement specification. A small residual artifact of the EMI can still be seen at 100 Hz. This is an example of supressing EMI "just enough" to allow accurate capture of the data of interest. The EMI could be supressed farther, e.g., to allow measurements to lower frequencies, but the mitigation means would be more complex and more costly. The lower measurement goal of this example was specified as 1 kHz, and the response of Fig. 6 easily meets this requirement.

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To demonstrate that this EMI management is not dependent on the actual test article, the response of a nominal 250 µOhm CVR shown in Fig. 1 was recorded, and is shown in Fig. 7.

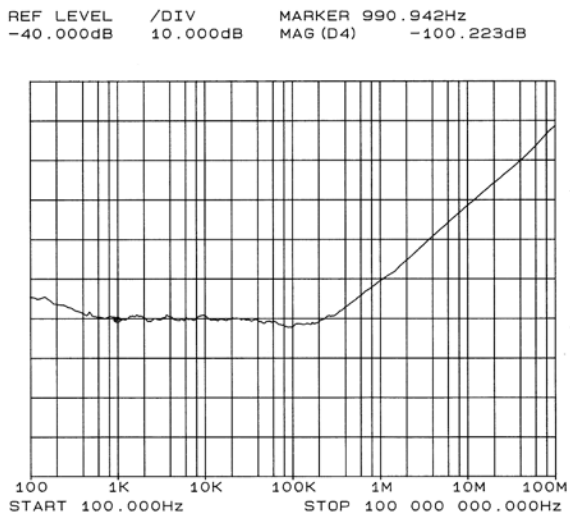

Figure 7: 243.3 µOhm CVR Response.

The DC resistance of this test article is 243.3 µOhms. At 1 kHz the impedance is 243.7 µOhms showing good agreement with the DC value.[2] Again in Fig. 7 the residual EMI artifact is seen at 100 Hz.

This specific CVR was selected for this example due to the network zero in the frequency response at nominally 200 kHz. This response characteristic is due to the equivalent series inductance of this CVR. This is an inherent characteristic of the sensor, and is not due to poor shielding effectiveness or EMI influencing the measurement. Below this zero frequency, this sensor is linear responding with a nominal 243.7 µOhm transimpedance, and above the zero frequency it responds as a derivative sensor.

For pulsed signals, this sensor will provide true representation of the pulse edges for transition times longer than nominally 1 µs. And for faster pulses the derivative response will differentiate the edges resulting in overshoot. This sensor and its response will be used again below in an actual measurement example.

Another real-life EMI example is a case where the author was asked to investigate why a high-power CVR was providing exceptionally-low readings of current in a simple MAINS current measurement. The simplified installation configuration is shown in Fig. 8.

The system configuration comprises a single-phase MAINS source supplying a load with the load return communicated through a CVR and returning to the source. Resistor R1 is the resistance of the MAINS bus work from the CVR to the source, R2 is the resistance of the oscilloscope power-cable safety ground from the oscilloscope to the source return and service bond, and Rsh is the resistance of the data-cable shield (~100 m RG58). And, the CVR device was found to actually be installed as shown in Fig. 8.

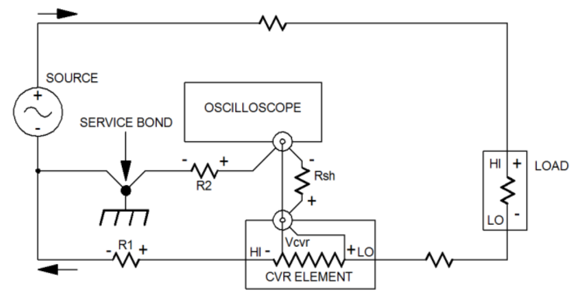

Figure 8: Actual Real-Life CVR Installation.

When the author examined the test data, not only was the CVR indicating a low current, but the sign of the current was inverted from that expected implying that current was actually flowing in reverse through the load, which could not occur in this test. And, since the CVR is such a simple sensor that one simply cannot use wrong, this was remarkable. But this was an obvious clue to the author as to the root cause of this errant reading. The root cause was simple EMI, but again not quite what one would typically recognize as EMI. The equivalent circuit of the measurement configuration of Fig. 8 is shown in Fig. 9.

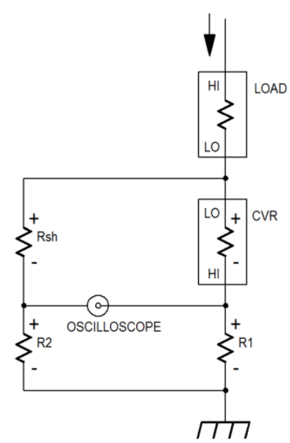

Figure 9: Measurement Equivalent Circuit.

Examining Fig. 9, it is seen that the resistors Rsh, R2, the CVR and R1 form a simple bridge configuration. Therefore, if the ratio of the data-cable shield resistance Rsh to the oscilloscope safety-ground resistance R2 were made exactly equal to the ratio of the CVR resistance to the bus-work resistance R1, not only would the indicated current be low, it would be exactly zero for any load current. This would not be a very good measurement of the load current!

And, since this is a simple bridge configuration, the sign of the indicted current at the oscilloscope can be

2. A network analyzer is not typically considered a high-accuracy instrument, perhaps ~0.1 dB, or on the order of 1 percent. The very close agreement of this measurement with the high-accuracy DC resistance measurement is coincidental.

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either true or inverted based on the relative values of the four resistances. It was this parasitic bridge configuration that resulted in the indicated current in the actual test being both low and inverted. It was simply a coincidence that the reversed installation of the CVR and the resistance ratios combined to indicate reverse current flow.

So, what does this example have to do with EMI? There is no EMI here! Or is there? First, it is noticed that there is the much-feared ground loop. Specifically the path from the service bond, through the bus-work resistance R1, through the CVR element, through the data cable shield resistance Rsh to the oscilloscope, and through the oscilloscope safety ground R2 returning to the service bond is a loop, a ground loop. However, since there are no external fields penetrating this loop, there is no problem since no loop currents can be induced.

The error results from a parasitic current, or in other words, EMI. This current is the current that flows in the data-cable shield resistance. The potential developed across the combined resistance of R1 and the CVR resistance drives current into the series combination of Rsh and R2. This results in shield current in the data-cable shield. This in turn results in a voltage drop across the data-cable shield. However, there is no corresponding voltage drop on the center conductor of the data cable. Therefore, the oscilloscope displayed data is in error by an amount equal to the voltage developed on the data-cable shield due to the shield current.

It may be argued that this is not really an example of EMI, but rather simply an example of poor instrumentation configuration. But, is not any case of EMI contamination a result of poor instrumentation configuration? Consider that instead of the source current causing the error in this example, a magnetic field linking the ground loop resulted in the same shield-current signal. There would be little argument that this would be a case of EMI contamination. Since the error is the same in both cases, both cases represent EMI contamination, and both fit the author's definition above.

This type of EMI can prove to be rather difficult to mitigate if not well understood. For example, consider that the ground loop is recognized, and it is simply *assumed* that the error is due external magnetic-field coupling to this loop, and accordingly various types of shielding are implemented. In fact, no amount of shielding will mitigate this EMI since it is not the result of a radiated emission, but rather is the result of a conducted emission. And, the conducted emission is due to the measurement configuration itself, and not from some external source.

This EMI could be mitigated simply by removing R2 opening the ground-return path from the oscilloscope to the facility ground, i.e., breaking the ground loop. This would very effectively eliminate the corrupting current in the data-cable shield, at least at low frequencies. However, R2 is the oscilloscope electrical safety ground, and which may not be broken under any circumstances.

It may be argued that this EMI problem may be mitigated by simply adding an isolation transformer to power the oscilloscope. However, electrical codes require all equipment grounds to be bonded together, so a bond is required across the isolation transformer, again completing the ground loop.

An obvious solution is a battery-operated oscilloscope totally floating with respect to the facility ground. This *may* work. But consider that this is a digital oscilloscope (as was the case in this real-life example), and that it has a digital output signal cable communicating the digital data to a host computer, and that this cable is a typical shielded digital data cable (which was also the case in this example). This digital data cable now again completes the ground loop, but here, in a large facility, the loop is likely very much larger than the original loop resulting in not only higher risk due to the conducted emission, but now has the increased risk of radiated emission is added.

Now, as the reader has likely concluded, the *obvious* root cause of the error in the CVR data is simply that the CVR is improperly connected in Fig. 8, indeed simply connected in reverse, and that the error is not truly due to EMI, but rather due simply to an incorrect implementation of the CVR. So, the CVR is so simple that one *almost* cannot use it wrong.

Figure 10 shows the CVR connected "correctly," specifically with its low terminal returning to the source. So, now life is good, and now confident that the CVR measurements are accurate, operations are resumed.

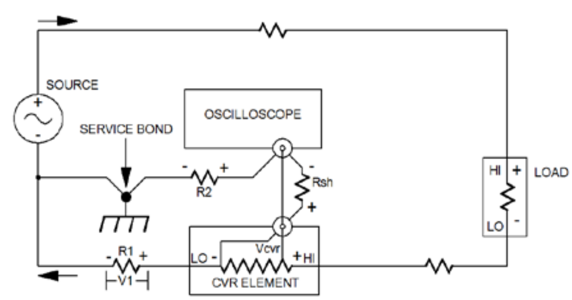

Figure 10: Another Real-Life CVR Installation.

To demonstrate that this configuration in Fig. 10 is now correct, and that the error introduced due to the improper installation of the CVR in Fig. 8 is now fully resolved, the instrumentation engineer performs a very simple qualification test with the following parameters:

Qualification-Test Parameters:

CVR = 100 μΩ,

R1 = ~65 μΩ, R2 = ~100 mΩ, Rsh = ~1 Ω,

Test Current = 1000 A P-P

The 1000 A P-P test current is applied, and the oscilloscope signal observed. The signal expected with the 1000 A P-P test current and the 100 μOhm CVR is 100 mV P-P. However, the oscilloscope display is found to be 159 mV P-P erroneously indicating that the current

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is 1590 A P-P. Again, the error is due to the current flowing in the data-cable shield. Installing the CVR "correctly" has not eliminated this EMI contamination.

If instead of actually preforming this qualification test, it was *assumed* that the issue had been resolved, and if an experiment specified a 1000 A load current, for example the current in a bending magnet in an accelerator, with 1000 A indicated at the instrumentation, the actual current would be 629 A. This could prove rather embarrassing if the beam happily escaped through the wall of the beam pipe due to an improper steering current.

So, the CVR is actually a very simple sensor where it is very easy to use it wrong, due to EMI.

These examples using a very simple sensor very clearly demonstrate the EMI issues caused by shield currents. And, these EMI issues extend from true DC to RF. In trying to eliminate the EMI corruption as seen in Fig. 3, if one is not aware of these currents, it would be very difficult to eliminate the EMI effects. So in cases of EMI in cables, ***it's all about the current – pretty much!***

SHIELDED-CABLE PROPERTIES

Two common terms used to specify cable-shielding properties are "shielding effectiveness" and "transfer impedance." Shielding effectiveness is typically defined in terms of fields, and therefore is often difficult to apply in real applications. However, transfer impedance is defined simply as the ratio of the potential developed on the signal conductors with respect to the shield, due to a current flowing on the shield, to the shield current. Both of these parameters may be directly measured.

Figure 11 shows the basic models for transfer impedance and shielding effectiveness. Note that no grounds are shown. Simply, there is a shield current, and a potential across the length of the shield. It is of no consequence how this current and potential are introduced, or whether the current is due to the potential, or the potential is due to the current. It is only of interest that these shield signals are present.

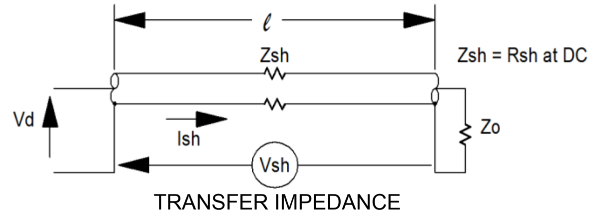
The transfer impedance is typically specified in units of Ohms per unit length. Shielding effectiveness is typically specified in terms of the ratio of fields, and specified in dB. The models for measuring both transfer impedance and shielding effectiveness, and the relationship between these two parameters, are also shown in Fig. 11.

Another useful cable-shield parameter is the Shield Reduction Factor K_r [5,6] defined simply as the ratio of the complex signal-conductor voltage induced by a voltage across the shield, to that complex shield voltage.

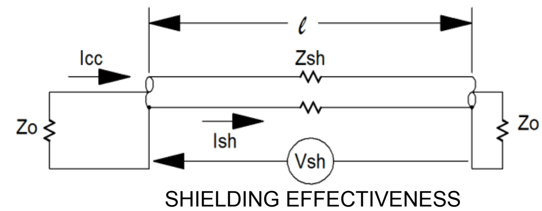
$$K_r \equiv {}^{V_d}/_{V_{sh}} = \frac{Z_t \cdot I_{sh} \cdot l}{Z_{sh} \cdot I_{sh} \cdot l} = \frac{(R_t + j\omega L_t) \cdot I_{sh} \cdot l}{(R_{sh} + j\omega L_{sh}) \cdot I_{sh} \cdot l}$$

But at DC, Z_t reduces to R_{sh}, so: $Z_t = (R_{sh} + j\omega L_t) \cdot l$

$$K_r = \frac{(R_{sh} + j\omega L_t)}{(R_{sh} + j\omega L_{sh})}$$



$$Z_t(l) \equiv {}^{V_d}/_{I_{sh} \cdot l} \quad \left[{}^{Ohms}/_{m}\right]$$



$$SE = 20log_{10}\left({}^{2 \cdot Z_o}/_{Z_t \cdot l}\right) = 20log_{10}\left({}^{I_{sh}}/_{I_{cc}}\right)[dB]$$

Figure 11: Cable Shielding Definitions [7]

At DC, K_r is unity, and there is no reduction provided by the shield. With frequency, the response characteristic will depend on the placement of the poles and zeros in the K_r expression. The simulated response of a nominal 2 m length of RG400 is shown in Fig. 12 expressed in terms of transfer impedance as a function of frequency.

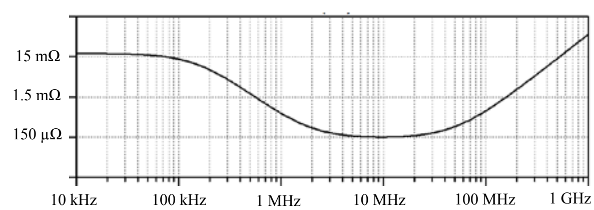


Figure 12: Simulated Z_t of 2 m RG400.

In Fig. 12 it is seen that Z_t is simply the shield resistance from DC to nominally 100 kHz, and therefor K_r is unity. With increased frequency, the Z_t first drops in magnitude, flattens, and then increases with a first-order response. This complex response is typical of all shielded cables, although the location of the poles and zeros will vary as a function of the shield construction.

A second network zero seen in Fig. 12 at nominally 30 MHz. This is due to leakage through the less than perfect shielding properties of the braided shield.

Terms like transfer impedance and shielding effectiveness are useful parameters to compare different materials, but just how does EMI outside a shielded cable actually couple to the signal conductors? It is not as mysterious as it is often portrayed. Figure 13 shows two models for two general sensor configurations.

The upper model of Fig. 13 is that of a low-resistance sensor, such as a magnetic-loop (B-Dot) beam position monitor. The lower model is that of a high-impedance sensor, such as a wire-scanner sense wire.

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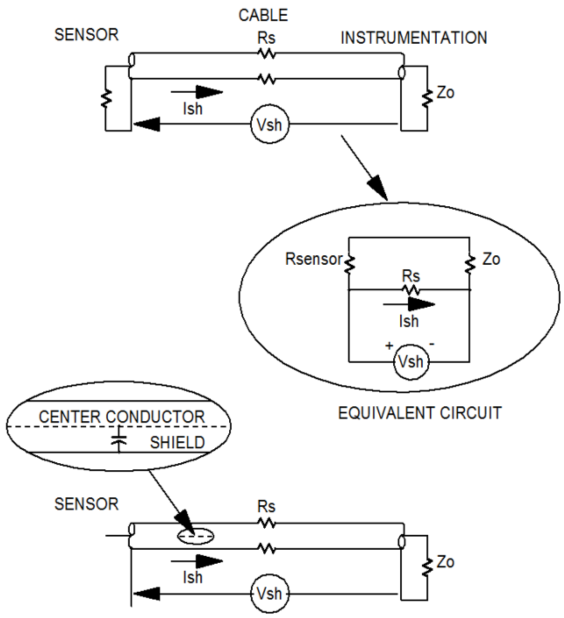

Figure 13: EMI Coupling into Shielded Cable.

The equivalent circuit of the upper model clearly shows that the source impedance and the load impedance (signal-conductor resistance is not shown) form a simple voltage divider driven by the shield voltage. This communicates shield voltage to the load.

It may seem that the lower model is immune to the effects of the shield voltage due to the open-circuit sensor. However, the capacitive coupling from the shield to the signal conductor form a reactive voltage divider comprising the cable capacitance and the load resistance again driven by the shield voltage that results in coupling of shield voltages to the signal conductor.

Figure 13 therefore demonstrates that the coupling of the EMI signal on the shield of a cable is very simply communicated to the signal conductor by simple voltage divider action.

EMI MITIGATION APPROACHES

As noted above, all EMI management is unique to each specific task. However, there are some general approaches that are useful to review.

Filtering

Filtering can be a very effective means of mitigating EMI, particularly were the EMI frequency signature is significantly out-of-band from the actual signals of interest, or presents as a very narrow spectral impulse, such as a radio station. As noted above, one should only utilize the bandwidth necessary to competently pass the signals of interest.

The means of applying a filter function must be carefully considered. For example, the actual instrumentation electronics itself is typically designed to band-limit signals to control noise by including a filter. Typically such a filter is placed at or near the analog output of the signal-processing path to effectively band limit all noise contributions, both that in the actual signal, e.g., EMI, as well as that inherent in the signal-processing path, e.g., thermal and shot noise.

For analog signal capture with such as an oscilloscope utilized to capture the analog data, in an attempt to minimize EMI, it is a common practice to add a "noise filter" immediately at the input to the oscilloscope. In cases of digital signal processing within the data channel itself, which is becoming quite common, it is a common practice to digitally filter the digital representation of the signal to provide band limiting. These are examples of types of post filtering.

Such post filtering does indeed band limit all noise at the output of the instrumentation signal-processing path. However this is not typically a very effective means of managing EMI, and can result in very puzzling data corruption. Although the noise is band limited at the output, there is no control of the signals input to the instrumentation. Where the EMI signals are out-of band with respect to the signals of interest, they are not observed. And where these signals are extremely high compared to the sensitivity of the data channel, the input circuitry can be easily driven out of both its normal-mode range and its common-mode range by the EMI signal. When this occurs, it may not be detectible in the instrumentation output signals since the actual EMI content at the output of the signal-processing path is removed by the post filter. However, the input circuitry is directly exposed to both the magnitude and spectral content of the EMI signal totally unfiltered.

This overdrive of the input circuitry of the instrumentation channel will result in non-linear response to the data signals. For less severe overdrive, one effect is that the channel gain appears mysteriously low. But in severe cases of overdrive, the data signals may be totally obscured as the input circuitry is driven hard into saturation at the frequencies of the EMI signal. Since the post filter removes all witness of the EMI signal, there is no evidence of an EMI contamination.

A real-life example is a typical field-mapping process where a very wide-bandwidth electric-field sensor was being used to observe signals over comparatively narrow frequency range using a network analyzer. The specific network analyzer being used had a frequency range of 9 kHz to 8.5 GHz. The frequency range of interest in the field-mapping task was 100 kHz to 100 MHz. The network analyzer frequency range is quite sufficient to capture the spectrum of interest. A comparatively low-level mapping signal was used, nominally 1 V/m, to prevent interference with nearby receivers as the network analyzer signal was swept over the test frequency range. To minimize noise to allow effective capture of the low-level mapping signal, the resolution bandwidth of the network analyzer was set to 1 Hz.

However, when the field mapping was complete, the results deviated very substantially from that expected. What was unknown about this environment was that there are a number of high-level RF sources, i.e., RF

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transmitters, operating nominally above 1 GHz in the vicinity, but that are not part of the actual facility being mapped, so these sources were unknown to the test personnel.

The signals from these sources are very effectively captured by the sensor, and since the frequency range of the network analyzer extends to 8.5 GHz, these signals pass directly into the network analyzer input into the first mixer. The network analyzer input circuitry is driven deep into limiting by these unknown signals.[3] The response to the in-band signals becomes extremely nonlinear resulting in inexplicable data records.

The foreign signals are true EMI. Although these signals are out-of-band with respect to the signals of interest, they still represent very serious EMI contamination since they unknowingly pass directly into the input of the instrumentation. The 1 Hz resolution bandwidth utilized is totally ineffective in controlling this EMI since this filter is a post-filter process, and typically is even applied after several heterodyne conversions within the network analyzer, or simply applied digitally in contemporary instruments. And, since the EMI is far out-of-band with respect to the spectrum of interest, it cannot be seen in the data records.

Based on experience, the author suspected out-of-band EMI. To do a "quick" diagnosis of the root cause of the unusual data records, the author utilized the network analyzer input attenuators. These attenuators are immediately at the input of the network analyzer and specifically before the first mixer or any active circuitry, and therefore attenuate all input-signal frequency components equally before the signal is presented to the input circuitry.

As the attenuators were engaged, it was observed that the output signal level did not follow the attenuation. For example, when a 10 dB attenuator was engaged, the signal level only dropped ~3 dB. This is due to the fact that even with the 10 dB attenuator, the input to the network analyzer was still being driven into limiting by the EMI signal, but simply somewhat less so.

One could of course add enough attenuation to reduce the EMI sufficiently low that the network analyzer input is no longer driven into nonlinear operation, but the actual signal then could not be observed.

In this case of out-of-band EMI contamination, once diagnosed, there was clearly no means to mitigate the EMI at the actual source, e.g., the offending RF transmitters. Therefore, the mitigation was necessary in the data acquisition. This issue was resolved by adding a sharp-cutoff low-pass filter with a corner frequency above 100 MHz, but below 1 GHz, at the input to the network analyzer thereby sufficiently reducing the EMI signals at the network analyzer input to prevent driving the network analyzer into nonlinear operation.

This specific real-life example of EMI contamination may seem a rather isolated example, and not really applicable in "typical" systems. However, the author has encountered this very EMI contamination in numerous cases. And, this type of EMI corruption is very insidious since it is for all practical purposes totally invisible. If one is not familiar with this type of EMI contamination, solving this type of EMI issue can prove very difficult.

The only reason that any problem was suspected at all in the field-mapping task of this example was that the nature of the facility had been very accurately modeled, and the field map had been very accurately computed analytically. The specific purpose of the physical mapping was to confirm the analytical predictions. When the test results did not match that expected from the analytical predictions, only then was some corrupting influence suspected. If this had been simply a task to map the field with no guidance as to what to expect, the errant data would have been accepted as accurate.

Capacitive Coupling

An approach that is occasionally used is full capacitive coupling of all of the data-cable conductors, including the shield. For example, at the point of measurement with a shielded cable, all the signal conductors and the shield would be capacitively coupled to the sensor. This of course will block any DC EMI, and it may be effective in blocking the MAINS first harmonic, but generally this approach is totally ineffective in eliminating higher frequency EMI components since these are simply passed through the capacitance with little of no attenuation.

Transformer Coupling

Total isolation seems the most logical approach to provide electrical isolation to reduce EMI. Transformer coupling provides near total isolation. However, inter-winding capacitive coupling allows high-frequency EMI to couple through the transformer. Also, the DC and low-frequency signal components are lost.

For wide-bandwidth applications, the coupling transformer must be carefully designed to competently pass the RF signals of interest while providing an adequate lower -3 dB frequency, and provide electric-field shielding between the primary and secondary, and magnetic shielding as well. These are often conflicting requirements in the design of the transformer. In general, suitable transformers may not be available as commercial parts, and therefore must be designed for the specific task. Transformer design, and specifically wide bandwidth RF transformer design, is in general a rather specialized art.

Fiber-Optic Signaling

Fiber-optic isolation also seems an attractive mitigation approach. And this can be quite effective in applications where EMI is extremely high, such as in electromagnetic-pulse environments.

However, fiber-optic systems tend to be costly and somewhat complex, and typically do not provide response to DC. Additionally, typically the optical transmitter at the point of measurement must be powered, which requires some type of power source having very high

3. These out-of-band signals can easily be of sufficient magnitude to damage the sensitive input circuitry of instruments such as network analyzers and spectrum analyzers.

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isolation, not only with respect to the instrumented system, but also with respect to the AC MAINS. Also, where a large number of channels are needed, fiber-optics can be a very costly approach.

Balanced Signalling and Twisted Pairs

A very useful approach to management of EMI is the use of balanced signals, e.g., as utilized in digital networks using standard unshielded, twisted pair ("UTP"). However, although the signal is accurately presented as the differential signal between the two conductors of the pair, EMI may, and often does, introduce such high common-mode signals that the receiver is driven far out of its useful common-mode range.

Since a UTP cable has no shield, the question of how to ground a cable shield is not an issue. But since UTP has no shield, the opportunities for mitigating EMI are severely reduced.

EMI mitigation in many applications, such as typical office environments, is provided by the use of coupling transformers in the communication equipment. However, since any DC signal component is lost with transformer coupling, a specific digital signal encoding that has a zero DC component, such as 8b10b, must be utilized.

This is not necessarily a difficult constraint to meet, but if a coupling transformer is arbitrarily introduced in an attempt to solve some EMI issue in a digital signal path, and the digital signaling does not have a zero DC component, very odd results can occur, such as random corruption of the received data with certain symbol sequences where the DC error results in the inability of the receiver to competently decode the digital signal.

And again the root cause of this data corruption is essentially invisible, and therefore extremely difficult to diagnose if one is not aware of this possible root cause.

In cases such as this, one could spend an inordinate amount of time trying to solve the data-corruption issue by further reducing EMI, but unsuccessfully. The actual original EMI corruption may have been very effectively eliminated by the introduction of the transformer isolation, but due to the nature of the signaling protocol, a totally different problem was introduced unrelated to EMI. Accordingly, further EMI reduction will have no effect in solving the data-corruption issue, and may even worsen the data corruption. This can be a very frustrating exercise.

Shielded Cabling

Shielded cable is perhaps the most common mitigation means utilized to control EMI. Shields *can be* effective for both multi-conductor cables as well as basic coaxial cables. And, for RF signals above even a few kilohertz, coaxial cabling is typically required to preserve signal integrity.

However, as reviewed above, any current that flows on the shield due to EMI excitation will to some extent couple EMI into the signal path. Cables with high shielding effectiveness are typically specified, but often the shielding effectiveness is never high enough. Also, cables having the lowest possible transfer impedance, such as with solid shields, may be utilized, but here too often the transfer impedance is never low enough. Even where the shield is solid, and even if many skin depths thick, EMI current on the shield can couple into the signal path. So, just having a "very good" cable will not assure elimination of EMI coupling.

Triaxial Cabling

Triaxial cables can be very effective in controlling EMI. The two shields of the triaxial configuration are electrically independent, as opposed to double-shield configurations. There are often lively discussions concerning how to "ground" the shield of even simple shielded coaxial cables. And the discussions become even more interesting when the second independent shield of the traixial configuration is introduced. It is not unusual to see both shields of a triaxial cable simply tied together and "grounded" in some manner thought to be optimal. This configuration effectively converts the triaxial configuration to a double-shield configuration, as provided in such as RG400, RG223, and numerous others including the class of cabling utilizing a combination of a wrapped foil shields and a braided shields.

If implemented effectively, the outer shield of a traixial cable carries virtually all the EMI current that would normally present on the shield of the actual signal path, eliminating, or at least greatly reducing, corrupting shield current on the signal-path shield. However, in many applications the legacy environment may not provide a useful means to use triaxial cabling effectively.

Steel Conduit

An excellent means of EMI mitigation is the use of steel conduits to carry both source and signal cabling, but in separated conduits. Such a conduit provides both another independent layer of shielding many skin depths thick, and also acts as a choke tending to reduce common-mode currents on its internal conductors at low frequencies.

The question still arises as to grounding of the conduit. In some cases, such as conduits carrying MAINS conductors, grounding is specified by safety codes. In legacy facilities the actual grounding configuration of conduits may be unknown. For example, where conduits pass through walls and floors, are the conduits bonded to the structural steel of the facility?

Also, it is often suggested that the low impedance of the conduct will eliminate "ground potentials" between the ends of the conduit. However, this is not typically the case. The impedance of the conduit is not really all that low, and particularly at higher frequencies. Also, the conduit effectively forms a ground loop with nearby grounds, such as facility structural steel, ground mats, counterpoise, etc., and this ground loop is formed even if the conduit is not "grounded" at all due to capacitive coupling to grounded structures.

Common-Mode Isolator

As stated previously, "it's all about the current – pretty much." Currents that flow on the outside of a shielded cable will couple to the signal conductors as demonstrated in the real-life examples above. In general the end-point potentials between the ends of a shielded cable are more of less fixed and cannot be effectively reduced. This is true for both electric-field coupling, i.e., antenna-type coupling, and magnetic-field coupling, i.e., ground loops. And this is also true of virtually all conducted emissions as well.

In the examples above reviewing transfer impedance and shielding effectiveness, no actual grounding of the cable shields is shown. All the analyses are based simply on the fact that shield currents and potentials are present on the cable shield. How the currents and potentials are introduced on the shield is of no consequence. It is only of concern that such signals are present.

To reduce the EMI coupled to the signal conductors, the shield currents must be reduced. This may be accomplished in some cases by selective grounding of the cable shield, but in a large extended facility, it must be expected that the ground structure is not equipotential. Also, even if there are no intentional grounds, capacitive coupling will still introduce ground coupling. And, in the case of unshielded cabling, such as UTP, there are no cable shields.

One means to reduce shield currents is to increase the shield impedance. This actually seems counterintuitive based on the earlier review of transfer impedance where it is implied that the shield impedance should be made as low as possible. However, that reduction of shield impedance was based simply on some current flowing in the shield. Reducing the shield impedance tends to reduce the potential developed on the shield, and in turn reduces the potential coupled to the signal conductors.

Alternately, if the shield current can be reduced, the coupling is also reduced. An example of this approach is grounding of a signal-cable shield only at one end. The shield impedance is effectively made infinite, but only for low frequencies. Such single-ended grounding eliminates direct conducted susceptibility, but higher frequencies still couple through capacitive coupling and electric-field coupling. Also, this is ineffective if there is direct coupling of the signal conductors to grounded structures, such as grounded sensors and grounded instrumentation. And again, in the case of such as UTP, there is no shield to be utilized in any manner.

One approach that can prove very effective in the management of EMI for both shielded and unshielded cabling is the use of the common-mode isolator ("CMI"). The CMI is perhaps the least complex, least costly, and least difficult to implement of all EMI suppression approaches. Because of these properties, it is a very useful device to implement in the initial efforts to control EMI where EMI issues are encountered in legacy environments, and also a useful device to consider in new facility designs as well as simply an inexpensive EMI-management measure.

The CMI is nothing more than a very simple 1:1 turns-ratio transformer. There are many different CMI configurations, but perhaps the simplest is shown in Fig. 14.

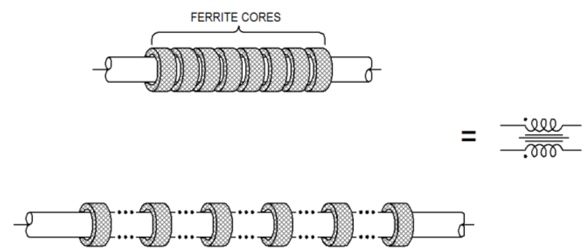

Figure 14: Examples of Common-Mode Isolators.

The CMI configuration of Fig. 14 comprises a number of high-permeability ferrite cores threaded onto the signal cable to be protected. The cores may be placed in close proximity as in the upper model, or placed periodically along the cable as in the lower model. The author uses both of these configurations in virtually all instrumentation in electromagnetic-pulse ("EMP") tests where the pulsed fields are extremely high, even approaching the breakdown of air, and with very fast transition times on the order of several nanoseconds.

The CMI actually provides two services. As noted, it increases the shield impedance which tends to reduce shield currents. But also, the CMI forces the voltage along the shield and signal conductors to be equal by adding mutual inductance. As a result, any AC potential above the lower cut-off frequency of the CMI that is introduced into the measurement due to shield voltage is also introduced in series with the signal conductors effectively subtracting the shield potential from the measured signal. This can be seen in the models of Fig. 11. In both models, if there is a shield voltage, all of part of this voltage will appear on the signal conductor. However, if a voltage source exactly equal to the shield voltage is placed in series with the signal path, the effect of the shield voltage is eliminated.

To objectively demonstrate the value of the CMI in a real-life example, the measurement of Fig. 5 was repeated both without and with a CMI. These measurements are shown in Fig. 15.

The upper trace in Fig. 15 is the same as that of Fig. 5. Any signal spectral content below nominally 100 kHz will be seriously compromised by the EMI introduced due to the shield currents in the signal cables.

A simple CMI similar to that of the upper model in Fig. 14 was placed in the source signal cable.[4] The lower trace in Fig. 15 is the resulting response with the CMI in place.

4. This CMI comprises a nominal 10 cm length to 0.250 semi-rigid 50-Ohm cable, terminated in female Type-N connectors, and with ten high-permeability cores placed on the cable.

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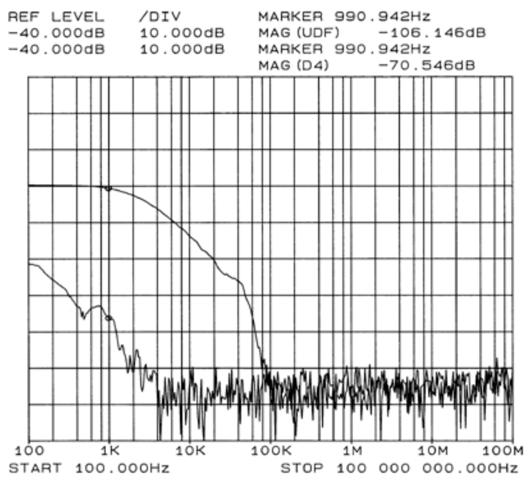


Figure 15: Performance of Common-Mode Isolator.

The CMI has very significantly reduced the EMI well below that without the CMI. At nominally 2 kHz, the EMI artifact has been reduced by almost 50 dB. And, at the 1 kHz lower measurement specification from the example above, the EMI is reduced by more than 36 dB.

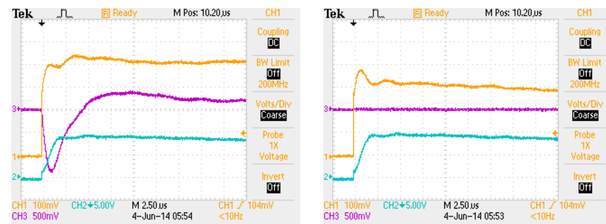
As another real-life example, specifically in a time-domain measurement, the author constructed a simple pulse generator capable of delivering a nominally square current pulse having a rise time on the order of 500 ηs, a pulse width of ~50 µs, and a peak current of ~1600 A into a short circuit. The leading edge of the pulse exhibits a good first-order response with no overshoot, and the pulse exhibits a nominal ~10-percent droop over the pulse width.

This pulse generator was battery operated to assure a fully isolated source, and configured to drive the 250 µOhm CVR characterized in Fig. 7 above. The CVR was "correctly" installed such that the common terminal of the CVR and that of the pulser were common.[5] The CVR output was connected to one input of an oscilloscope with a nominal 1 m length of RG400, and terminated in 50 Ohms at the oscilloscope. A standard oscilloscope probe was connected to a second channel, the probe ground lead was tied directly to the common of the CVR output connector, and the probe was place "near" the pulse generator output switch to capacitively couple a sample of the switch transition voltage simply to provide a trigger and a time reference. The common node at the pulser and CVR was not tied to anything other than the signal cables. Finally, a 1 Ohm wide-bandwidth current transformer was placed on the signal cable from the CVR to the oscilloscope, and connected to a third channel of the oscilloscope to witness any common-mode current flowing on the CVR cable.

5. At these high currents, the current-carrying structures are quite large. In this simple experiment, the ground structure is a brass plate 12 mm thick and ~150 mm, wide and nominally ~300 mm total length. Also, the entire experimental structure is configured as a parallel-plate transmission line with ~0.2 mm dielectric spacing to minimize the parasitic inductance of the system.

From the frequency response of the CVR shown in Fig. 7, the high-frequency response exhibits a response zero at nominally 200 kHz. Therefore, the response expected of the CVR to the pulsed current signal is a slight overshoot at the leading edge of the response due to the CVR response zero, and then a reasonably smooth response with a nominal ten-percent droop due to the pulse-generator characteristic. The response of the CVR in this configuration is shown in the first image in Fig. 16.

Incorrect Measurement / Correct Measurement



Without Common-Mode Isolator / With Common-Mode Isolator

Figure 16: Example of Common-Mode Isolation.

The upper trace (400 A/Div) in the images of Fig. 16 is the CVR output, the lower trace is the timing reference, and the center trace (500 mA/Div) is the current-transformer output.

The response shown in the first image is not at all that expected. The peak current is nominally 1600 A as expected based on the known pulse-generator characteristics and the known CVR low-frequency characteristics. However, there is no overshoot at the leading edge, and indeed there is a noticeable dribble-up. This is not an acceptable response. Also, the late-time response shows virtually no droop in the signal. This too is an unacceptable response since it is known that the input pulse exhibits droop, and that the CVR response is well behaved below its response zero at 200 kHz.

The current transformer shows a nominal 1.3 A common-mode current flowing on the CVR signal cable. It is this current, a true EMI signal, that is corrupting the measurement.

The CMI used for the measurement in Fig. 15 has a nominal 250 µH inductance, and was installed in the CVR signal line and same signals captured. These signals with the CMI are shown in the second image of Fig. 16. In this image the peak current is ~1400A with overshoot seen on the leading edge of the CVR response witnessing the CVR zero, as expected. Also, there is a nominal ten-percent droop witnessing the droop in the pulse-generator response, also as expected. And, the current on the CVR signal cable is virtually zero.[6]

Therefore, the first image in Fig. 16 is seriously in error. But the only reason that the author is aware that this is an erroneous measurement is that the characteristics of the CVR, specifically the frequency response, and that of the pulse shape of the pulse

6. The actual current was observed as <5 mA, but for ease of visual comparison of the two images, the same scales are used for both.

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generator, specifically the transition time and pulse droop, are known. The author designed this experiment specifically to demonstrate how EMI can unknowingly corrupt a very simple measurement, even in a well-controlled bench environment.

If one were unaware of these CVR and pulse-generator parameters, and for example were tasked to capture the response of the pulse generator using this CVR, and no CMI were utilized, the very poor result would be obtained suggesting that the pulse generator exhibits a small degree of dribble-up on the leading edge, but provides a reasonably flat late-time characteristic, both incorrect. Similarly, if the task were instead to capture the CVR response using the pulse generator, the erroneous result would totally conceal the CVR zero, also a serious error.

The logical question to ask is: How is this EMI error introduced in such a simple and apparently well-controlled experiment? It's the current, not "pretty much," but absolutely. Clearly as shown in the first image of Fig. 16, a substantial common-mode current flows on the shield of the CVR signal cable. And this current induces a corresponding potential into the measurement as reviewed above.

But, how is this current introduced on the signal cable in this "well-controlled" experiment? The answer is obvious, well almost. It is due to a ground loop. The loop path is from the oscilloscope ground at the connection of the CVR signal cable, to the CVR output connector common, to the oscilloscope probe ground lead, and back to the oscilloscope ground through the probe-cable shield.

But how is this ground loop excited? This is a case of radiated susceptibility. The magnetic field due to the pulser current links to this ground loop. This results in a current in the loop, and therefore a common-mode current in the CVR signal cable. If there were no second ground connection, i.e., no probe ground, there would be no path to create a common-mode current, and virtually all shield common-mode current would be eliminated. With the second ground connected, a loop is created resulting in current flow from the CVR output common to the oscilloscope. This current is a common-mode current, and in both the CVR signal cable as well the oscilloscope-probe cable.

This then raises the question of "to ground or not to ground?" For example, if the probe ground were disconnected, the ground-loop problem would be eliminated, and a true response would be observed for the CVR signal. However, if the probe ground lead were disconnected, the voltage measurement of the probe would be severely compromised. So, for competent measurement of both the current and voltage signals, both the signal-line ground path and the probe ground path must be fully intact. In other words, one must live with this ground loop. Also note that in this example, the safety ground of the oscilloscope is of no consequence.

Therefore, rather than attempting to eliminate the ground loop with heroic measures, such as perhaps a fiber-optic data system, the CMI was utilized to highly attenuate the common-mode current around the loop, and to force any shield voltage artifact across the signal-line shield to be introduced in series with the signal on the signal conductor.

This very basic experiment demonstrates both how easily an apparently simple measurement using a very simple sensor can be quite seriously compromised by EMI, even in an apparently well-controlled experimental environment, and how effective the simple CMI is in eliminating the EMI influence.

The basic concept of the CMI is not that unusual. Figure 17 is a photograph of an actual CMI installed in an operational system.

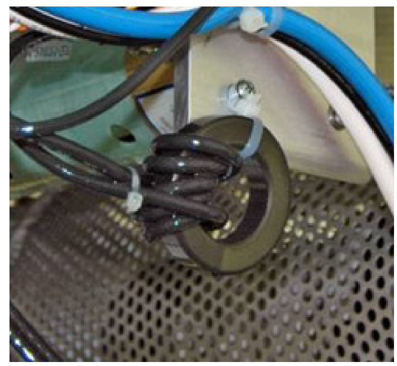

Figure 17: Multi-Turn Common-Mode Isolator.

This CMI utilizes six turns on a large high-permeability ferrite core. The advantage of this multi-turn configuration is that the inductance, and in turn the impedance, increases as turns squared. Therefore, at first examination, to achieve the same result as this CMI but using the configurations of Fig. 14, it would seem that 36 cores would be required. However, the much smaller cores of Fig. 14 will typically exhibit an inductance factor greater than that of the larger core of Fig. 17. In practice, the same inductance may be achieved with perhaps ten to fifteen of the smaller cores.

However, there is a critical deficiency in the CMI of Figure 17. The cable from the two isolated sides of the CMI are tightly tied together. This results in high capacitive coupling shunting around the CMI, and at higher frequencies, the effect of the CMI is diminished, or even totally frustrated. In the configurations of Fig. 14, the two CMI ports remain very well isolated.

Also, another subtle issue with the CMI in Fig. 17 is the resistivity of the ferrite core. Typically a Manganese-Zinc ("MnZn") material, or even a high-permeability metallic material in a tape-wound core, would be utilized to provide the highest-possible inductance. The MnZn materials, and more so metallic core materials, exhibit a very low resistivity. Therefore, the core itself provides a capacitive coupling path among all the turns. This too can seriously compromise the performance of this CMI at higher frequencies. A Nickel-Zinc ("NiZn") material, that typically exhibits a much higher resistivity, could be utilized, but the inductance factor of the NiZn materials is very much lower than that of the MnZn materials

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resulting in a much lower inductance reducing the effectiveness of the CMI at lower frequencies.

The low resistivity of the MnZn core material is of little consequence in the CMI configurations of Fig. 14.

The common-mode isolator is equally as simple as the current-viewing resistor, but as with the current-viewing resistor, it can be implemented incorrectly regardless of its simplicity.

A FINAL OBSERVATION

Where did all this 180 Hz (or 150 Hz) come from?

The author has been asked on numerous occasions to help resolve a puzzling EMI issue were the signals are contaminated with a predominately 180 Hz artifact. And, the author is assured that: “We have nothing operating at 180 Hz!”

This artifact is due to summing of the third-harmonic currents of the 3φ AC Power MAINS. This is easily seen with a bit of trigonometry.

Sum of Fundamental Phase Current I^1 :

$$I^1{}_{SUM} \equiv I^1{}_A + I^1{}_B + I^1{}_C$$
$$|I^1{}_A| = |I^1{}_B| = |I^1{}_C| \equiv |I^1{}_0|$$
$$I^1{}_A = |I^1{}_0| \angle 0$$
$$I^1{}_B = |I^1{}_0| \angle 120$$
$$I^1{}_C = |I^1{}_0| \angle 240$$
$$I^1{}_{SUM} = 0$$

Sum of Third-Harmonic Phase Current I^3 :

$$I^3{}_{SUM} \equiv I^3{}_A + I^3{}_B + I^3{}_C$$
$$|I^3{}_A| = |I^3{}_B| = |I^3{}_C| \equiv |I^3{}_0|$$
$$I^3{}_A = |I^3{}_0| \angle 0$$
$$I^3{}_B = |I^3{}_0| \angle 360 = |I^3{}_B| \angle 0$$
$$I^3{}_C = |I^3{}_0| \angle 720 = |I^3{}_C| \angle 0$$

$$I^3{}_{SUM} = 3 \cdot |I^3{}_0| \angle 0$$

These simple computations show that even if all phase currents of all harmonics are perfectly balanced, which is rarely the case, the vector sum of the harmonic phase currents do not all sum to zero. Specifically, in this example, it is seen that the magnitudes of the three third-harmonic currents all add directly resulting in a third-harmonic current the sum of which is a factor of three greater than that of each phase. This is also true of the various higher-order harmonics.

This third-harmonic current flows in the neutral of the 3φ MAINS distribution, and since the MAINS neutral is connected to ground at some point, this current can, and commonly does, escape into the ground system. Also, the higher frequencies of these harmonic currents result in a higher degree of coupling into surrounding structures, such as building structures and instrumentation cabling.

A very quick and simple assessment to determine if some EMI signal is MAINS related is by using an oscilloscope. While observing the EMI signal, simply switch the oscilloscope trigger to “LINE TRIGGER.” Anything that “stands still” is related to the MAINS distribution, either directly or indirectly.

CONCLUSIONS

Electromagnetic Interference, EMI, is eventually encountered by anyone working with data acquisition systems, data communication systems, and virtually any other system requiring high-quality communication of information. There is no cookbook solution, and no one-size-fits-all approach to mitigating EMI. Every EMI issue is unique, and all EMI mitigation must be engineered for each specific application. The goal of EMI mitigation is to reduce the effects sufficiently to reduce interference to acceptable levels. It is not typically economical, or even feasible, to totally eliminate EMI.

EMI is commonly due to coupling from external sources, such as MAINS equipment, RF sources such as radio transmitters, and many other sources, often which cannot be identified. But often the interference is due to internal coupling from such as switch-mode power supplies, or even high-speed digital electronics. And, EMI may be introduced by the measurement-system itself. The root cause of EMI is often unrecognized, and the source misdiagnosed leading to substantial difficulty in achieving adequate mitigation. The nature and root cause of interference signals must be very well understood before any attempt at mitigation is begun. And this is why virtually all EMI solutions must be engineered to each specific case. And: *It’s all about the current – pretty much!*

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