Short Course on Isolators and FM Antennas

Introduction

Isolators have been around for more than 50 years, and during that time have been used in applications across a wide electromagnetic spectrum. Until recently, however, they have not been widely used in the FM band, and the uses that did exist did not require the development of units that could handle more than a few hundred watts. Now, as stations begin to go on the air with digital radio in ever increasing numbers, FM isolators are receiving a great deal of attention as a key component in a number of IBOC installations. Early deployment has been limited by the low power ratings of the available units, but power capacity is rising quickly as manufacturers devote time and resources to developing isolators specifically to address the needs of the new FM market. On the other side of the fence, RF engineers are rapidly familiarizing themselves with the principles of isolators and their advantages and limitations.

As with any emerging technology, integrating various components of the FM IBOC transmission chain has had both successes and setbacks. Isolators have been involved in both. As with all test sites, some of the early deployments could be said to be more educational than successful, but as often as not these setbacks were not so much the fault of the isolators themselves as of the inexperience of the engineers deploying them and their imperfect understanding of the environment in which the isolators were to operate.

Had the early units been more robust, some of these problems might not have been so apparent. However, the relatively low power rating of the early units meant that in many cases they were being used at or near capacity, so that even small miscalculations in the isolation and return losses of a system were critical. The two immediate results were that designing higher-power isolators became a priority, and that antenna engineers took a long, hard look at the design of their radiators and the techniques they used for achieving isolation.

As this paper is being written, isolators are available that can handle combined forward and reflected power of 2 kW or more. This limit is expected to continue to increase. Contrast this to the 500 watts that was considered the practical limit for stable operation only a few years ago. "Practical" has been an important consideration along the way, as advances in power rating sometimes came with conditions that limited the usefulness of the units. Size, weight, and cooling requirements that might be suitable at some sites made the units impractical at others. For example, in at least one application, an isolator capable of handling the return power of the station was only efficient enough to do so when it was warmed up. While this might be fine for some systems, this would probably not be the best equipment to employ at a cold-start auxiliary site.

As the technology evolves, isolator problems are becoming less frequent, but they have left many with the impression that isolators should be avoided if at all possible. Some equipment manufacturers have even gone so far as to promote that their equipment is superior because it doesn't require the use of an isolator. In other cases, manufacturers have been slow to admit that problems were the result of the poor electrical performance of their radiators and the inability of the isolators then available to compensate adequately. While no one would argue in favor of retaining unnecessary components, it would be unfortunate for viable implementation strategies not to be considered simply because of an imperfect understanding of how the equipment is designed to perform.

This paper should give the reader a basic knowledge of how and why isolators are used in IBOC implementation and a general understanding of how they relate to other components of the broadcast chain, particularly the antenna. Hopefully the reader will come away with enough understanding of how these systems work to be able to understand why isolators are suitable and successful in some installations, while not in other, similar, systems.

Basics of isolators

An isolator is comprised of a circulator and a load. The load is a simple dummy load identical to those found in many applications in broadcasting. As part of an isolator, its design criteria are the same as for any load - to comfortably handle the maximum power it is expected to see without overheating.

The circulator is the heart of the isolator and the component that limits its performance. It is the circulator that is the focus of research and design to enhance the capabilities of isolators.

Circulators come in many varieties and configurations. The isolators being supplied for most IBOC installations use distributed constant style circulators with three legs.

In a circulator, the signal moves between legs in only one circular direction, giving the device its name. While it is theoretically possible for the signal originating at any given leg to reach any other leg, complete circulation is interrupted by the existence of one high-impedance leg, which traps energy trying to move across it and shunts it off to a dummy load. Thus it is possible to configure the circulator to allow the signal from the transmitter to flow freely out the adjacent antenna leg, but energy returning through the antenna leg is interrupted before it can reach the transmitter leg.

This is shown in Fig. 1. The signal from the digital transmitter is fed into the isolator at Leg 1. It flows out Leg 2 on the transmission line toward the antenna, its further progress being thwarted by the high impedance of Leg 3. At the same time, any signal from the antenna enters the circulator at Leg 2 and is directed to the dummy load at Leg 3. This ability of isolators to trap on-frequency signals headed in the wrong direction and shunt them harmlessly off to a dummy load is key to a number of IBOC analog-digital combining strategies which employ separate digital and analog transmission paths, and where the combining method does not afford at least 35 dB of isolation between the digital and analog transmitters.

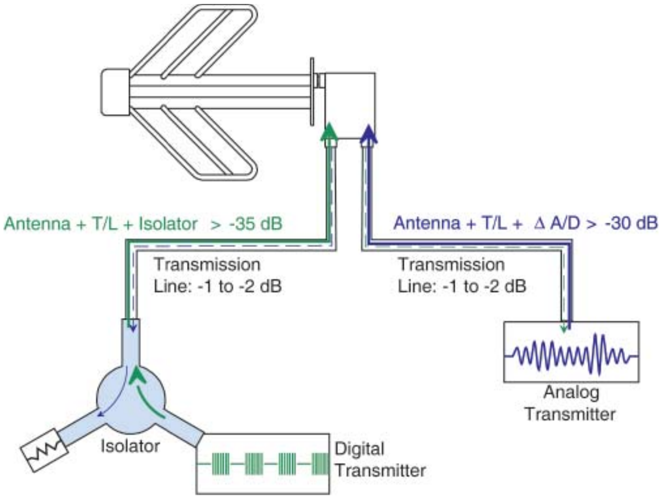

Figure 1. Basic Isolator Configuration

Strategies that combine analog and digital signals in antenna radiators, or use separate analog and digital radiators in close proximity, do not have enough isolation between the analog and digital components, and require isolators. These are among the most popular IBOC implementation strategies because they minimize the size and cost of the digital transmitter and reduce the energy wasted. Isolators are not used where the analog and digital signals are already combined in the transmitter (low level), combined through a hybrid providing at least 35 dB of isolation (mid-level), or combined using a coupler/injector providing at least 35 dB of isolation (high level).

20 dB differential between analog and digital signals

Under the current IBOC standard, a station's digital signal is launched 20 dB below the analog signal. However, this does not mean that there is a 20 dB differential between the analog and digital signals in an IBOC transmission system. An exact 20 dB differential will only occur if both signals are feeding antennas or portions of the same antenna that have the same gain. In practice, this usually occurs only when they are feeding the exact same radiators. If the signals do not see the same antenna gain, then the output of one transmitter (usually the digital) will need to be increased to compensate.

However, for simplicity, we will assume a 20 dB differential between the signals and that the signals feed common radiators. There is validity in using this assumption, as in some respects this represents the worst case. Where the signals are most apt to have different gains (interleaved analog - digital antennas and spatially separated antennas), isolation is likely to be greatest. Differences in elevation patterns, physical distance between the radiators, and alternation of the polarization of the radiators all enhance isolation. In practical terms for the isolator, this means that although an increase in digital transmitter power to compensate for lower gain may require a larger circulator, this increase will be mitigated by a reduction in analog power flowing back toward the transmitter, in turn reducing the size of the load required.

As we work through the discussion of system isolation requirements below, keep in mind that the transmitters (most likely the digital) might require a few extra dB of isolation to compensate for differences in gain.

Isolation and transmitters

How much isolation is sufficient is a matter of some debate, but for reasons explained below it is generally considered to be in the range of 30 dB of isolation of the analog transmitter from the digital signal, and 35 dB for the digital transmitter from the analog signal. Isolation is achieved by a combination of factors, including differences in transmitter power, transmission line losses, isolation between radiators or inherent to the design of a radiator, isolation inherent in combining components such as hybrids or couplers, or the addition of an isolator.

Combining an analog signal and a digital signal in an IBOC installation differs from combining two analog-only signals in a classic multi-station installation in two important respects: first, the digital and analog signals are adjacent, with the digital signals located right at both edges of the analog channel, compared with an 800-kHz separation in the closest analog-to-analog schemes. Second, in analog-to-analog combining schemes, both transmitters react similarly to signals from the other transmitter, so that unwanted signals must be suppressed to the same degree. In analog-to-digital combining, the transmitters react differently to each other's signal, so each side of the transmission path is best considered separately.

Isolating the digital transmitter from the analog signal

Digital transmitters typically "fold back" when confronted with interfering signals approximately 15 dB below carrier. This is equivalent to a 1.5:1 VSWR. Because the analog power is initially about 20 dB higher than the digital, in order for the digital transmitter to operate correctly the analog signal needs to be suppressed by a total of 15 + 20 = 35 dB. An isolator can accomplish 26 dB of this suppression, requiring the remaining 9 dB be achieved in the antenna and transmission line. While digital-only transmission lines need not be large to handle the power of a digital transmitter, they are usually oversized to minimize losses and in turn the size and cost of the digital transmitter. Therefore, the line doesn't usually contribute more than a dB or two to the total isolation. This leaves 7 - 8 dB of analog energy to be accommodated by the isolation of the antenna. This level of isolation is realistic, given that separately-fed radiators regularly see values of 20 dB or more, and even the worst performing commonly-fed radiators can be expected to achieve a minimum of 9 dB.

Without an isolator, the antenna would need to achieve 33 dB or more of isolation in order to prevent the digital transmitter from folding back. With the isolator in place, this value drops into ranges regularly achieved by today's antennas. Antenna manufacturers are working hard to improve the isolation characteristics of their antennas, and are promoting each advancement. This has left some with the impression that isolators are an unproven, unstable component and are to be avoided. However, the use of isolators remains a powerful and cost effective means of achieving sufficient isolation.

As we will see below, the issue is the maximum power handling capacity of current isolator designs and the ease with which a poorly-designed antenna can overwhelm that capacity. Many of the early problems in deploying systems with isolators arose not from problems with the isolators themselves, but rather from poor understanding of the characteristics of the radiators. With a properly designed radiator, isolators are a cost effective, reliable way to increase the total isolation of a system.

Isolating the analog transmitter from the digital signal

The system design goal for isolating the analog transmitter from the digital signal is about 30 dB below the analog carrier. Since the digital power is 20 dB below the analog to begin with, this leaves only the remaining 30 - 20 = 10 dB to be achieved by the transmission system. As with the digital side of the equation, the analog transmission line can probably be counted on for a dB or two, and the antenna for at least 9 dB.

Therefore, it is usually taken for granted that if the antenna meets the isolation requirements of the digital transmitter, the analog transmitter will be also be satisfied. The 5-dB advantage in the isolation required is the reason why isolators are not needed between the analog transmitter and the antenna. This is fortunate, as almost all analog transmitters would overpower today's circulators.

It should be mentioned that the 30 dB of total isolation is considered a very safe value and no one knows for sure what is actually required. To date, no one we spoke with could cite installation problems with the digital affecting the analog, so no one knows for sure at what point problems would actually occur.

Sizing an isolator

General

Sizing an isolator correctly is a two step operation: the sizing of the circulator, and the sizing of the load. The circulator must be sized to handle the sum of the digital transmitter power passing through the circulator to the antenna, and the unattenuated analog power reaching the circulator from the antenna. The unattenuated analog power level alone determines the size of the load.

Example 1

Let's take the example of a single station with an ERP of 6 kW, using a 4 bay, full-wave-spaced panel antenna with a power gain of 2.12.

In addition, let's assume that the analog and digital signals are broadcast over the same radiators of the panel and that these radiators receive the signals over separate transmission lines having insertion losses of 1 dB. Let's also assume in this example that the isolation between the analog and digital portions of the radiators is 20 dB.

The antenna in this example (Fig. 2) would require 2830 watts of analog power at its input to achieve the required ERP. Since the analog and digital portions of the antenna would have the same gain and the digital signal is launched 20 dB below the analog, the antenna would require 28 watts at the digital input. With 1 dB of attenuation in the transmission line, 35 watts of digital power would need to pass through the circulator on its way from the digital transmitter to the antenna. The antenna isolation of 20 dB means that 28 watts of analog power will travel down the digital transmission line, where it will be attenuated by 1 dB and arrive as 23 watts at the isolator. This means that the circulator must be sized to handle 35 + 23 = 58 watts, while the load must comfortably handle 23 watts.

This is a classic isolator application, and the circulator in this example will be running well within the capacity of even the oldest technology. This will be the case for the vast majority of class A stations and many class B stations that use medium- or high-gain antennas. Problems begin to arise with higher-power stations running medium- to high-power trans-

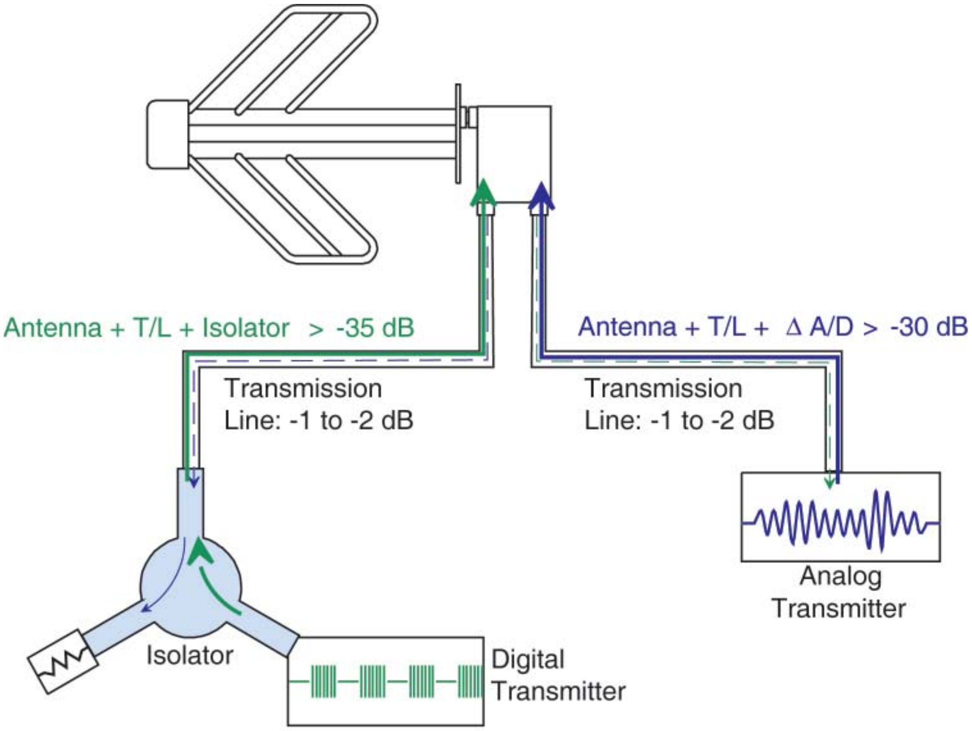

Figure 2. Single Antenna Fed by Analog and Digital with Isolator

mitters, and with installations where the antenna isolation is poor.

Example 2

Take the example above with the same assumptions, except with the analog ERP increased to 60 kW. The circulator now must be sized to handle approximately 580 watts and the load 230 watts. These power levels are well within the range of common loads, but until recently this was pushing the limit of circulators. The same size isolator components would also be required if the isolation of the antenna in the first example were only 10 dB instead of 20.

Multiple stations

Let's assume that the same panel antenna is being used for three different stations, fed through a three station balanced combiner (Fig. 3).

Example 3

For the sake of comparison, let's assume that each station has the same ERP of 60 kW and the same gain of 2.12. In this example, as in the previous one, the isolator located at the digital input port of each balanced combiner module will see approximately 580 watts through the circulator and 230 watts to the load, assuming that the isolation of the antenna at each frequency is 20 dB. This is true, even though there is approximately three times as much combined analog + digital power returning down the digital transmission line, because the analog power, not on frequency, will be attenuated by at least 50 dB by the combiner module itself.

It should be noted that each circulator in this installation will also receive a small amount of analog power arriving at the circulator directly from the analog input of the hybrid, but this will be very small, typically much less than 30 dB down from the analog transmitter power.

Multiple stations in the real world: different isolations

In the real world, the isolation of any three stations (unless they are very close in frequency) will differ, because it is not possible to build a radiator that achieves a completely flat isolation value at a reasonable power level across the entire 88-108 MHz FM band. Isolation can be optimized for any frequency or for a small, closely spaced group of frequencies; this is often done for broadband radiators that will only be used for one or two stations. However, when a radiator is being used for the entire band, the center frequency will typically have the best isolation values, and isolation will decrease significantly at each end of the band. How significantly it will decrease depends on how optimized the isolation is at center frequency. As the isolation value at the center of the band is increased, the isolation at the ends of the band will decrease. Similarly, optimizing the isolation at any given frequency will have a tendency to decrease isolation at other parts of the band disproportionately.

Experience has shown that a well-matched radiator, where the individual radiating elements also track each other closely electrically, can achieve an isolation differential between the center and the ends of the band as low as 6 dB. Poorly matched or poorly tracking radiators will have a much higher differential.

Example 4

If we revisit the example of the three station antenna above, except using 20 dB of isolation for Station A, 17 dB for Station B, and 14 dB for Station C, we will find that the isolator for Station A will see 580 watts through the circulator and 230 watts into the load. Station B will now see 798 watts through its circulator and 448 watts into its load, and Station C will see 1245 watts through its circulator and 895 watts into its load. Fig. 3 shows varying load sizes to emphasize this.

This shows that even with medium power stations operating on a high quality broadband panel antenna, we can expect some stations to approach the operating limits of conventional isolator technology, even as the other stations on the system are well within comfortable ranges. This is also an example of why antenna manufacturers are so concerned with antenna isolation.

As a side note, at Shively Labs we are often approached by engineers who are concerned that the reject loads on their combiners are hotter than on the other stations in the system. This example demonstrates why this is a normal operating state.

Poorly-matched radiators

Let's see what happens when we put a poorly matched radiator into the equation.

In a panel radiator, isolation corresponds directly to how well each dipole element of the radiator is matched across the entire FM band. The second component that radiator designers concern themselves with is how well the performance of each individual radiating element tracks the others electrically; that

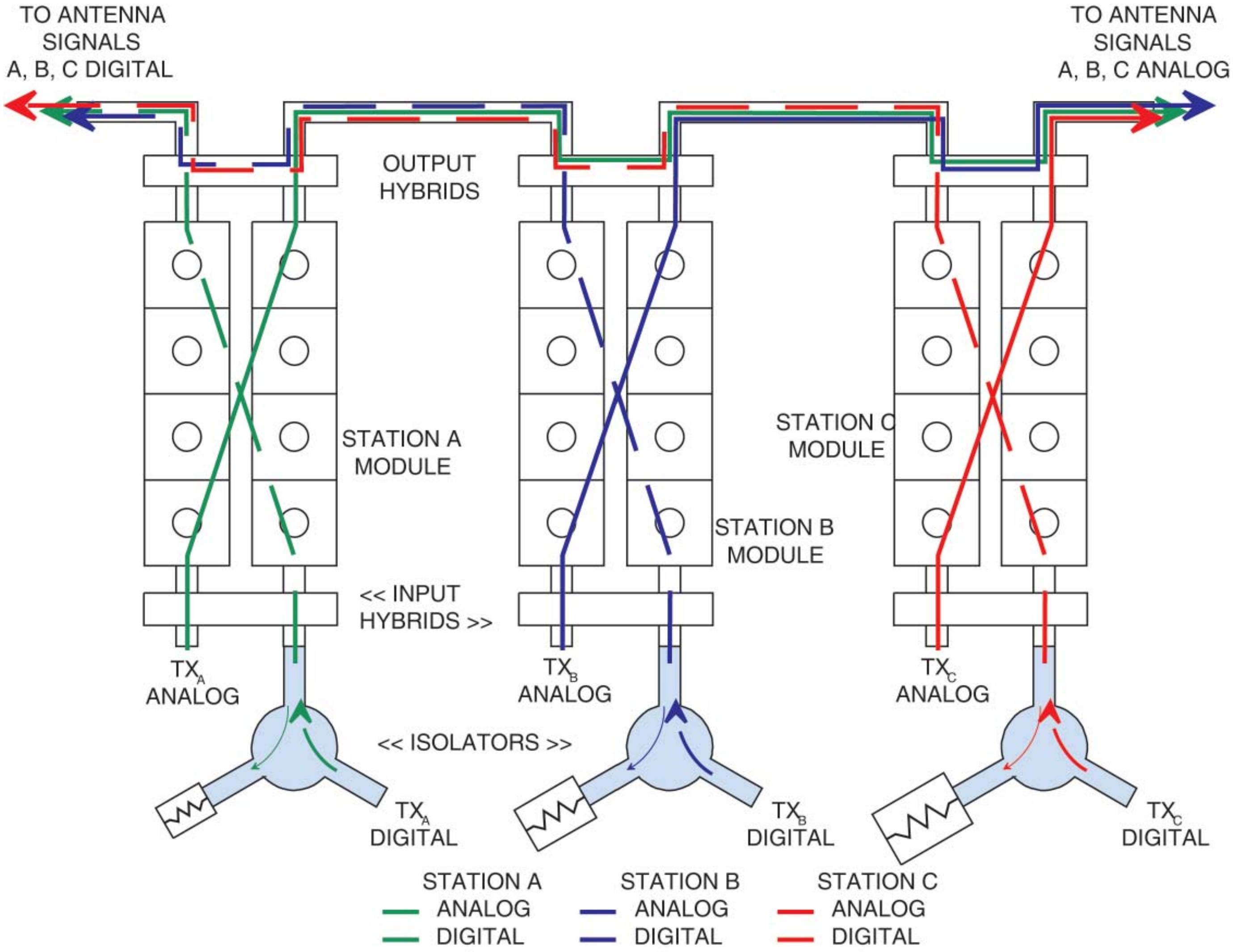

Figure 3. A Three-Station Digital-Analog System

is, how symmetrical the electrical response is between dipoles. Tracking can change with very subtle differences in the geometry of each element and its relationship to other components of the radiator and back plane.

Until recently, antenna designers have been primarily concerned with a single analog input for each radiator. Designers gained valuable bandwidth either by altering the internal feeds of the radiators, or by adding reflectors and rings external to the radiators. These reflectors and rings make it very difficult to produce a radiator where the radiating elements track well and are matched well across the band.

Until the introduction of analog-digital combining techniques that used the isolation port of the hybrid to accommodate the second feed, designers were not as concerned with the match as with the tracking. Adequate tracking enabled the excessive reflected power produced in poorly matched radiators to simply be shunted to the isolation port of the radiator hybrid, where it was either absorbed in a dummy load or reflected back into the radiator by a tuned short. Now that the load or short has been removed to accommodate the digital feed, this excessive reflected power passes through the hybrid port to the isolator where it could quickly overwhelm the capacity of the circulator.

Example 5

Returning to the example of the three-station balanced system, if the isolation of Station C is decreased only an additional 3 dB (9 dB down from optimum), its circulator will now need to accommodate 2136 watts of energy, and its load will see 1786 watts. This approaches the maximum capacity of circulators on the market today. Should the deviation in the radiator increase to something even greater than 9 dB, the lack of a viable circulator would mean that Station C would need to consider a different method of combining digital and analog signals.

Conclusion

Isolators are an important component in IBOC implementation. Engineers weighing the various implementation strategies need not only understand the capabilities and limitations of current isolator designs, but also have a realistic understanding of the needs of their systems. As the power handling capacity of FM isolators increases, they will become easier to integrate into new and existing systems. Until then, however, careful attention must be paid to the efficiencies of each system, particularly the antennas, to ensure that the isolator isn’t overloaded.