Considerations for -10 dBc IBOC Combined Station Side-mount Master FM Antenna Design

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Abstract

In recent years, the use of FM-IBOC is increasing along with the power levels of the OFDM sidebands from -20 dBc to -10 dBc. When combining multiple FM + IBOC stations into a single transmission system, proper consideration must be given to the antenna design to ensure reliable service. Sizing the components so they handle the extra power, choosing a radiator design to handle the extra bandwidth as well as the co-phased voltage additions must all be examined. This paper takes an in depth look at the impact -10 dBc IBOC has on multi-channel side-mount antenna system design. The focus is on the breakdown analysis procedure and discusses typical breakdown prevention methods as well as techniques to boost the voltage safety factor.

INTRODUCTION

It has been shown that voltage breakdown is a major limitation in high power multi-channel FM-IBOC transmission system design. Due to the fact that the pulse lengths of FM-IBOC are greater than the critical pulse length defining the CW condition, the OFDM carriers must be treated as CW. In doing so, the probability of co-phased voltage addition of multiple stations can be calculated as well as the number of probable events within a given time frame [1].

PEAK TO AVERAGE POWER RATIO

Defining the breakdown condition as the point where the co-phased voltages coincide to a level exceeding the PAPR used in the power and voltage handling calculations, the number of probable voltage breakdown events in a time frame is given by equation (1).

$$N_e = n \cdot Y \cdot B(e^{-PAPR_{linear}})^n \quad (1)$$

Where n is the number of combined stations, Y is the number of seconds in the given time frame, B is the bandwidth of an individual channel and PAPR is the peak to average power ratio. For a recommended time frame of 100 years and using the occupied bandwidth of the two sidebands in IBOC extended mode, MP2, the equation reduces to (2).

$$N_e = 6.09x10^{14} n \cdot (e^{-PAPR_{linear}})^n \quad (2)$$

If one voltage breakdown event in 100 years is an acceptable limit, then it can be shown that the relationship between the number of stations that need to be added in the voltage breakdown and power handling calculations and the PAPR of each station is given by equation (3).

$$PAPR_{dB} = 10log\left[-ln\left(\sqrt[n]{\frac{1}{6.09x10^{14}}}\right)\right] \quad (3)$$

If more than "n" stations with IBOC are being combined, the voltage additions must be handled differently. As described in reference [1], when combining multiple stations and the probability of PAPR exceedance drops below the threshold value, (in this case, 1 event in 100 years), the PAPR's used in the voltage addition calculation should be normalized back to the 1 in 100 year condition.

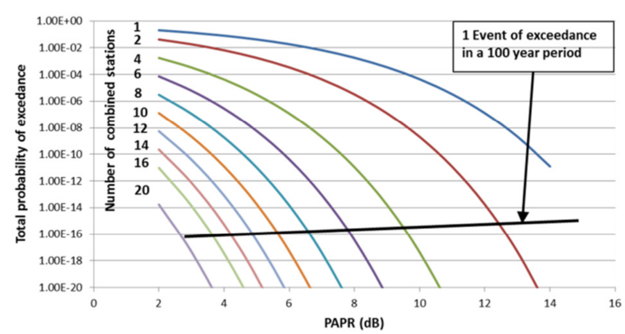

Figure 1: Recommended PAPR's to be used for total voltage handling calculations versus number of stations for a 1 time in 100 year probability of voltage breakdown. [1]

FM – IBOC COMBINING

The three methods of producing the IBOC hybrid FM signal are low level combining, high level combining, and space combining. Both high level combining and space combining require separate transmitters where low level combining or “common amplification” combine the outputs of the IBOC and FM exciter into a broadband linear amplifier. Of the methods, common amplification reduces the number of components and / or floor space in the broadcast chain and thus minimizes the impact to the broadcaster. With advances in common amplification transmitter technology, this approach seems to have become an attractive choice.

SPEARATE TRANSMITTERS VS. COMMON AMPLIFICATION

Advances in crest factor reduction in common amplification (FM+IBOC) transmitters allow the peaks of the HD carriers to be moved to the FM analog space, thus lowering the PAPR of the IBOC signal which does not occur with separate transmitters. Referring to Table 1, and using equation 3, the number of stations that must be included in the voltage and power handling calculations using full PAPR before a PAPR reduction factor can be applied can be calculated and is shown in Figure 2.

	PAPR for given IBOC level		
	-20 dBc	-14 dBc	-10 dBc
Separate Tx	5.5 dB	5.5 dB	5.5 dB
Common Tx	1.3 dB	2.3 dB	3.5 dB

Table 1: Recently published PAPR levels for different IBOC levels for both separate transmitters and common amplification transmitters.

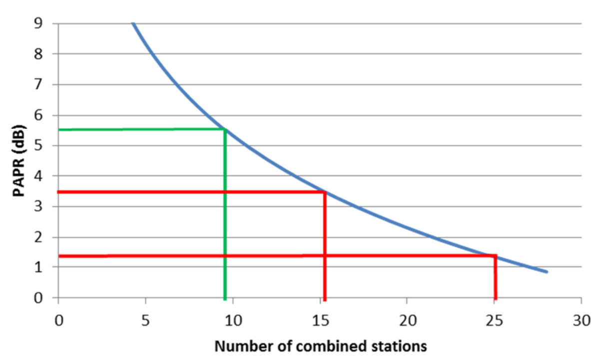

Figure 2: Number of combined stations that must be taken into account in the voltage and power handling calculations vs. PAPR of each station before a PAPR reduction factor can be applied.

As can be seen, if all the combined stations were to employ separate transmitters to add IBOC at -10 dBc with PAPR’s of 5.5 dB, then 10 stations must be included in the power and voltage handling calculations. If more than 10 stations exist on the system, only then can the PAPR reduction factor (the PAPR’s given in Figure 1), be used in the calculations. One the other hand, if all combined stations are using -10 dBc IBOC with low level combining having PAPR levels of 3.5 dB, 16 stations must be included in the voltage and power handling calculations before applying the PAPR reduction factor. It should be noted here that with possibly the exception of NY City, there is no other location in the country which can take advantage of a PAPR reduction factor for a large number of combined stations when using low level combining.

BANDWIDTH

Co-located multi-station combining, each with -10 dBc IBOC levels, not only implies high power but broadband operation as well. Broad bandwidth is not only necessary to accommodate channels with a wide frequency separation, but also to ensure a low quality factor (Q). Quality factor in its most fundamental form is:

$$Q = w\frac{energy\ stored}{average\ power\ disipated}$$

Low Q antennas are wideband and store less energy and therefore handle the extra power associated with -10 dBc IBOC with a higher safety margin. The antenna is perhaps the least understood component in the RF system when it comes to bandwidth. An electrically small antenna can be defined as having an aperture fitting within the radiansphere with a radius given by equation (4) where λ is the wavelength [2].

$$r = \frac{\lambda}{2\pi} \quad (4)$$

At FM frequencies this radius is approximately 20” in which most high power side mounted FM broadcast antennas elements manufactured today fit within. The quality factor (Q) for an electrically small circularly polarized antenna is given by equation (5) [3].

$$Q_{cp} = \frac{1}{2}\left[\frac{1}{k^3a^3} + \frac{2}{ka}\right] \quad (5)$$

Where k=$2\pi/\lambda$ and “a” is the occupied volume radius of the radiating element. Q is the inverse of the fractional bandwidth given by the well-known expression:

$$bw = \frac{VSWR - 1}{Q\sqrt{VSWR}} \qquad (6)$$

The above calculated bandwidth can be increased, at least in principle, using a matching network, but there exists a theoretical limitation. In 1950, R.M. Fano defined the fundamental bandwidth bounds on lossless passive matching networks for antennas to be: [4].

$$bw = \frac{\pi}{Q ln\left\{\frac{VSWR+1}{VSWR-1}\right\}} \qquad (7)$$

where the VSWR is the maximum allowable in the passband. Since equation (6) represents the normally obtained bandwidth, where equation (7) expresses the maximum realizable bandwidth that is theoretically achievable using matching techniques, a maximum bandwidth enlargement factor can be found by dividing the two quantities [5].

$$F = \frac{\pi\sqrt{VSWR}}{(VSWR-1) ln\left\{\frac{VSWR+1}{VSWR-1}\right\}} \qquad (8)$$

An obvious consequence of equations (5), (6) and (7) is that the maximum realizable bandwidth of the antenna is purely a function of its size. In order to handle the extra power and co-phased voltage stack-up of combined FM stations with -10 dBc IBOC, the antenna should be as large as possible. However, to keep the wind load to a minimum, the antenna should be as small as possible. Of course, the maximum theoretical bandwidth cannot be realized due to practical limitations. Inspection of equation (8) yields a minima at F=3.9. This minimum bandwidth enlargement factor practicality relates to a simple single stage matching transformer.

The lower bounds on the antenna elements Q provided by equation (5) have been found to be elusive to achieve in practice, (i.e. the Q is always higher and the bandwidth less than expected) [10]. One argument for practical designs having higher Q's than predicted is that the entire spherical volume is not utilized by the radiating element. To overcome this factor, the use of spheroidal functions instead of spherical functions has led to the Q dependence on the ratio of the major to minor axis of the bounding surface enclosing the element [10][11]. Refer to Figure 3.

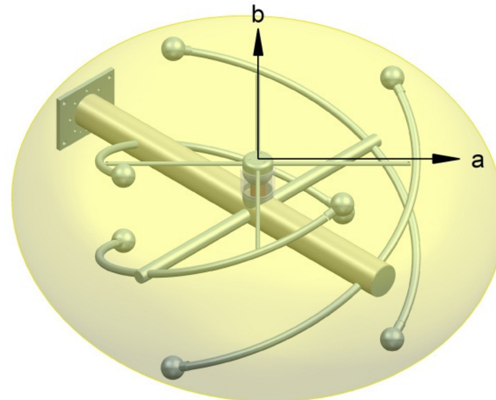

Figure 3: Full band circularly polarized side –mount quadrupole ring style antenna element fitting within an oblong bounded region.

For diameter/height (a/b) ratios less than 4, it has been shown that the spheroidal Q/spherical Q factor (Q'/Q) is equivalent to the (a/b) ratio [11]. The prior equations can be arranged to summarize the maximum bandwidth achievable by a circularly polarized radiator fitting within an oblong bounded region of (a/b) and matched through the use of a simple practical technique for a desired VSWR level; equation (9),

$$bw = 3.9 \cdot \left(\frac{VSWR - 1}{\frac{a}{2b}\left[\frac{1}{k^3a^3} + \frac{2}{ka}\right]\sqrt{VSWR}} \right) \qquad (9)$$

where a and b are the major and minor ellipse radii and k is $2\pi/\lambda$. For full FM band operation with a maximum allowable VSWR of 1.15:1 within the passband, the antenna shown in Figure 3 requires a diameter of 38" and height of 22". This has been verified both theoretically through simulation as well as measurements. Refer to Figure 4.

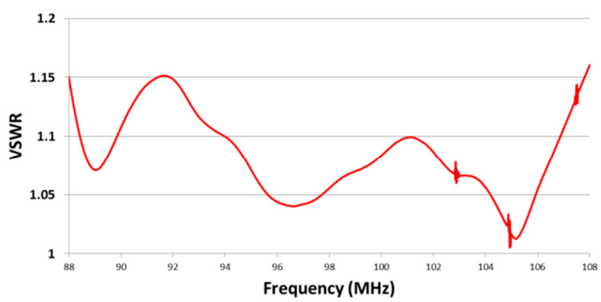

Figure 4: Measurement of a recently developed high power circularly polarized FM antenna validating the bandwidth / volume relationship developed in this paper.

Since increasing the antenna element size beyond the minimum volume required for the desired VSWR performance both increases the wind load and cost, methods to increase the power handling capability and decrease the probability of voltage breakdown due to co-phased voltage additions will now be discussed.

GEOMETRICAL CONSIDERATOINS

The electric field intensity near a conductor is inversely proportional to the radius of curvature of the surface and can be approximated by equation (10) where V is the applied voltage [6]. Refer to Figure 5.

$$E_m \approx \frac{2V}{r\,ln\left(1+\frac{4d}{r}\right)} \quad (10)$$

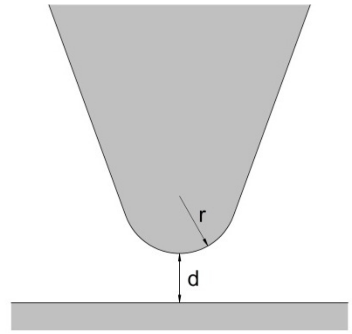

Figure 5

A sharp edge or point has a very small radius of curvature so the electric field near a sharp edge or point is very large and thus has a greater potential for breakdown of air and sparking [1]. Using the equations developed in [1], it can be shown that the maximum number of combined stations given a voltage safety factor, VSWR correction factor, known PAPR's for the IBOC levels of each station and the test voltage breakdown level of the component under analysis is given as equation (11).

$$n_{max} = \frac{V_{peak\,RF}}{SF\left(V_{p-analog} + V_{p-IBOC}\right)C_{VSWR}} \quad (11)$$

Through equations (10) and (11), the proportionality between the maximum number of stations that can be safely combined versus sharp edge radiuses is given by equation (12) and normalized in Figure 6.

$$n_{max} \propto r\,ln\left(1+\frac{1}{r}\right) \quad (12)$$

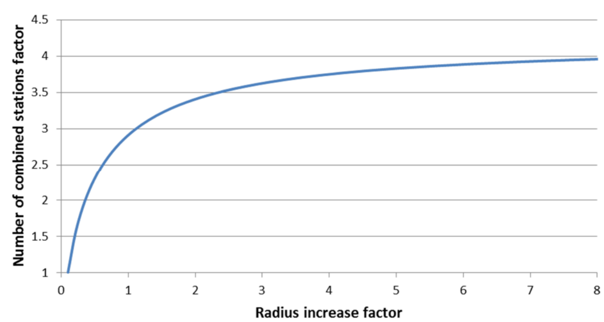

Figure 6: Relationship between increasing the radius of sharp edges and the maximum number of combined stations for a given voltage safety factor, and IBOC levels.

Figure 6 depicts the relationship between increasing the radius of sharp edges vs. the number of combined FM stations that can be applied to a component for a given voltage safety factor and IBOC level. It becomes apparent from this chart that radiuses have a significant impact of the number of allowable combined stations and a proper design with large radiuses can increase the number of allowed combined stations by a factor of 4.

PRESSURIZATION FACTOR

Peak power and voltage ratings can be increased by pressurization above atmospheric pressure levels by using dry air or nitrogen. A relation known as Paschen's law has been verified both experimentally and theoretically in the case of DC breakdown [8]. This is a fundamental statement of behavior of voltage breakdown of gases. As shown in equation (13), it states that the breakdown voltage is a function of the type of gas, (a, b are gas specific constants), the pressure (p) and the electrode spacing (d), but does not include frequency and pulse length.

$$V_B = \frac{apd}{ln(pd) + b} \quad (13)$$

It has been found that for pressures around one atmosphere (760 torr.), the electric field breakdown is relatively unaffected by change in frequency [8], but has been experimentally measured at 22.8 kV/cm in air [7], a much lower value than predicted by DC breakdown using Paschen's law. A more accurate method for analyzing ionization breakdown in an RF environment which involves a semi-analytical approach leads to equation (14), and can be used to calculate the air ionization breakdown threshold (electric field strength in RMS value, V/cm) as a function of frequency (Hz), pressure (torr) and pulse length (s) [12], [9].

$$E_p = 3.75p\left(1 + \frac{\omega^2}{25x10^{18}p^2}\right)^{1/2} x \left(\frac{10^6}{p^2 {L_{eff}}^2} + 6.4x10^4 + \frac{20}{p\tau_p}\right)^{3/16} \quad (14)$$

Where

$$p = p_0 \frac{273}{273 + T_0}$$

Where

$p_0 =$ Air pressure in torr

$T_o =$ Temperature in C

$\omega =$ Angular frequency

$L_{eff} =$ Effective diffusion length in cm. For practical purposes, one often approximates it as half of the gap size.

$\tau_p =$ Pulse length in seconds

Note that at one atmosphere (760 torr), one would get an electrical field strength of approximately 22.8 kV/cm. Doubling the atmospheric pressure, (which is equivalent to adding 15 psi), approximately doubles the air ionization breakdown threshold. Note that from equation (11), this also effectively doubles the number of combined stations that can be safely applied to the pressurized component.

PRACTICAL CONSIDERATIONS

Excessive theoretical analysis might help with initial design criteria and understanding why gaps breakdown, but won't provide accurate values for a given situation. An accepted method in determining the peak voltage and power rating of RF systems, transmission lines and antennas is to perform a DC Hi-Pot (High Potential) test on each component and relate the breakdown level to an RF condition. The Hi-Pot test consists of attaching electrodes to the inner and outer conductor and applying a DC voltage until breakdown occurs. The RF breakdown voltage is then calculated using equation (15), where 0.7 is an accepted industry rule of thumb number known as the DC to RF factor and is based on the previous DC to RF analysis.

$$V_{Peak\ RF} = .7xV_{DC} \quad (15)$$

Once the peak voltage breakdown point is known in a climate controlled setting, both correction factors and safety factors must be applied in order to assign a voltage and power rating to the component when used in its intended environment [1].

For illustration, DC Hi-Pot testing was conducted on three types of tap points used on quadrupole ring style side mount FM antennas such as the one shown in Figure 3.

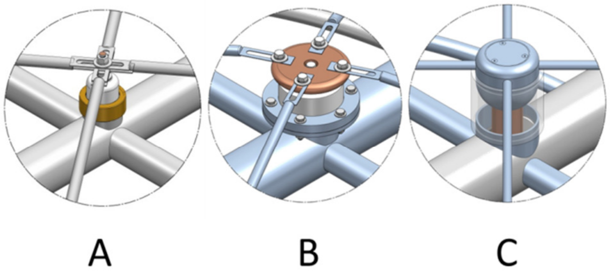

Figure 7: Tap point feed designs used on side mounted FM quadrupole ring style antennas. (A) Simple small diameter threaded inner. (B) Larger mushroom shaped tap point with rounded edges. (C) Spherical tap point with full radiuses and external pressure seal.

Results are shown in Figure 8.

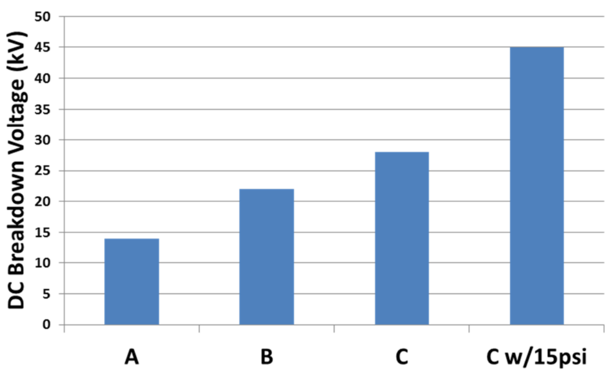

Figure 8: DC Hi-Pot testing results of tap point designs.

From equation (11), the number of allowed combined stations for a given power and IBOC level, voltage safety factor and VSWR, is proportional to the test Hi-Pot level. From the results obtained in this example, the combined channel capacity can be increased by a factor of over 3 times when going from a simple tap point design as the one shown in A of Figure 6 to a pressurized design similar to the one depicted in C. This is actually a conservative factor since the test with 15 psi of pressure only shows a 60% increase in the voltage breakdown. Theoretically this increase would have been expected to be near 100%, as given by equation (14). The discrepancy lies in the fact that the breakdown occurred external to the pressurized area of the test fixture not allowing the experiment to reach the full voltage capacity within the pressurized region.

CONCLUSION

Currently, voltage breakdown is one of the major limitations in high power multi-channel FM-IBOC transmission system design. Due to the fact that the pulse lengths of FM-IBOC are greater than the critical pulse length defining the CW condition, the OFDM carriers must be treated as CW. Lower PAPR's associated with common amplification eliminate the possibility of using a reduction factor for low probability of co-phased voltage additions from multiple combined stations. Typical breakdown prevention methods as well as techniques to boost the voltage safety factor can be summarized.

- Use larger bandwidths to reduce the stored energy in the radiator. Choose an antenna aperture size to accommodate the bandwidth without un-necessarily over sizing the components and increasing the wind load and cost.
- Reduce the maximum field strength in gaps by avoiding sharp edges and using rounded corners. Increasing the radius of small shape edges has a significant impact on the number of allowable combined stations limited by co-phased voltage additions.
- Employ pressurization. Doubling the atmospheric pressure effectively doubles the number of combined stations that can be put into a component limited by co-phased voltage additions.

Following these rules and applying the combination of analysis, test and experience allows FM antennas to be adequately designed to handle the extra power, bandwidth and co-phased voltage additions associated with combined -10 dBc IBOC operation.

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