-10 dBc IBOC at Combined Transmission Sites

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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. This provides a challenge to properly size the RF components so they handle the extra power. The situation becomes more complex when more than two stations are combined into one transmitting system. A power increase to -10 dBc IBOC on multi-channel systems has a substantial impact on the design of every component. This paper reviews how voltage peaks for combined stations are calculated and how RF component and antenna voltage and power handling is derived. The practical safety factors necessary to ensure reliable service are discussed for the RF system and transmission line as well as the antenna.*

Introduction

The traditional method of calculating peak powers is to determine, then add the peak voltages of each channel. If the combined voltage applied to a component is high enough, an RF breakdown or arc may result. An RF arc has the potential to severely damage RF components leading to costly down time and repairs for the broadcaster [1]. The purpose of the present work is to investigate the threshold condition for breakdown in FM-IBOC RF system components and apply safety factors for prevention. In particular, analytical expressions are obtained to analyze the safety factors when combining multiple stations into a single RF network.

Peak to Average Power Ratio

Transmitter manufactures are continually working on methods to reduce the peak to average power ratio (PAPR). The PAPR puts a stringent requirement on the power amplifier and reduces the efficiency in the sense that a higher input back off factor is needed before the peaks in the signal experience significant distortion due to the power amplifier nonlinearity. The IBOC OFDM signal in its compressed state has about 8 dB PAPR. Once passed through a power amplifier, the PAPR is reduced through compression to about 6 dB [9].

The Probability of Occurrence

The method of calculating peak powers for multi-station FM installations is not standardized among broadcast equipment manufactures. The conservative approach has always been to add the worst case voltages and size all components appropriately [1]. But what is the likelihood of this worst case event where all the voltage peaks within the channel and from all the combined stations must add constructively?

Orthogonal Frequency Division Multiplexing (OFDM) consists of several closely spaced orthogonal sub-carrier signals each individually modulated in both amplitude and phase. There is a finite probability that all of these carriers will add in phase at their max amplitude [1]. The dependence of breakdown field on pulse length and pulse repetition frequency as well as the guidelines used to determine if single pulse breakdown statistics can be used is well defined in reference [6]. The physics behind the ionization of air requires an understanding of the dynamic evolution and relaxation of the physical processes which determine the voltage breakdown and is beyond the scope of this paper. If the pulse duration is less than the defined critical pulse length, the amount of voltage required to induce breakdown increases as in the case of DVB-T. If the pulse length is greater than the critical pulse length, the breakdown condition is unaffected by pulse length and equal to the continuous wave (CW) condition.

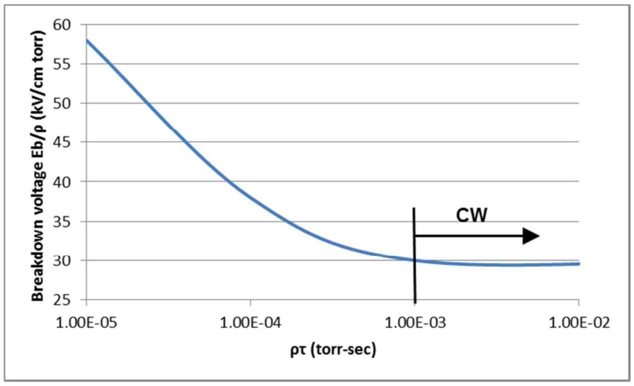

Figure 1: Threshold field for single pulse breakdown [6].

The single pulse breakdown condition should smoothly join the CW condition as the pulse length increases. The critical pulse length (τ_c) above which the breakdown condition is unaffected by pulse length and equal to the CW condition is given in equation (1), where p is the pressure in torr [6].

$$\tau_c = \frac{10^{-3}}{p} \quad (1)$$

At sea level where p=760 torr, the critical pulse length is 1.315 micro-seconds.

FM-IBOC is a broadcast of small OFDM side-bands added into the same channel as an analog FM broadcast. Adding the two side-bands together, the occupied bandwidth of a single IBOC broadcast is 139.092 kHz in mode MP1 and 193.316 kHz in MP2 or extended mode [7]. The pulse length (τ_p) can be approximated by equation (2) where n is the number of OFDM sub-carriers and Δf is the OFDM sub-carrier frequency spacing.

$$\tau_p \approx \frac{1}{n \cdot \Delta f} = \frac{1}{BW} \quad (2)$$

For extended mode MP2, the pulse length is 5.17 micro-seconds which is greater than the critical pulse length and therefore should be treated as CW for breakdown calculations.

It can be shown that the probability density function of a single OFDM signal is Rayleigh and is discussed extensively in reference [8]. The reference defines the exceedance probability (p_e) as the probability that a peak will exceed the PAPR and is given by equation (3).

$$p_e = e^{\left(\frac{-x^2}{2\sigma^2}\right)} = e^{-PAPR_{linear}} \quad (3)$$

Where x^2 represents the instantaneous power, and $2\sigma^2$ the mean power which equates to exp(-PAPR). According to the exceedance formula, if the individual OFDM signal is clipped at 6 dB, the probability of clipping taking place is .0187 or 1 in 50 chance of an occurrence or 5.9 x 10^7 seconds per year. If two channels are combined into a single transmission line and antenna, the probability of two clipped peaks coinciding is (.0187) x (.0187). In general, the total probability (p_t) of all peaks coinciding is given by equation (4) where n is the number of stations [8].

$$p_t = (p_e)^n \quad (4)$$

For multi-station operation, the total probable event time (t_e) within a 100 year period is given by:

$$t_e = p_t \cdot seconds\ in\ 100\ years \quad (5)$$

It cannot be said precisely how many exceedance events will take place within the given time period, however, the total duration (T_d) of each event will approximate to the reciprocal of the total occupied bandwidth and is given by equation (6) where n is the number of combined stations.

$$T_d = \frac{1}{n \cdot BW} \quad (6)$$

Therefore, the number of probable event occurrences (N_e) is given by equation (7).

$$N_e = t_e \cdot \frac{1}{T_d} \quad (7)$$

Table 1, Table 2 and Figure 2 show the number of expected events that will occur in a 100 year period for both a PAPR of 6 dB as well as 8 dB.

n	p_t	t_e (sec)	T_d (sec)	N_e
1	1.87E-02	5.89E+07	5.17E-06	1.14E+13
2	3.48E-04	1.10E+06	2.59E-06	4.25E+11
3	6.50E-06	2.05E+04	1.72E-06	1.19E+10
4	1.21E-07	3.83E+02	1.29E-06	2.96E+08
5	2.27E-09	7.15E+00	1.03E-06	6.91E+06
6	4.23E-11	1.33E-01	8.62E-07	1.55E+05
7	7.89E-13	2.49E-03	7.39E-07	3.37E+03
8	1.47E-14	4.65E-05	6.47E-07	7.19E+01
9	2.75E-16	8.67E-07	5.75E-07	1.51E+00
10	5.13E-18	1.62E-08	5.17E-07	3.13E-02
11	9.58E-20	3.02E-10	4.70E-07	6.43E-04
12	1.79E-21	5.64E-12	4.31E-07	1.31E-05

Table 1: Number of expected full in-phase voltage addition events of all FM-IBOC stations that will occur in a 100 year period with PAPR=6 dB where n is the number of combined stations.

n	ρ_t	t_e (sec)	T_d (sec)	N_e
1	1.82E-03	5.74E+06	5.17E-06	1.11E+12
2	3.31E-06	1.04E+04	2.59E-06	4.03E+09
3	6.02E-09	1.90E+01	1.72E-06	1.10E+07
4	1.09E-11	3.45E-02	1.29E-06	2.67E+04
5	1.99E-14	6.28E-05	1.03E-06	6.07E+01
6	3.62E-17	1.14E-07	8.62E-07	1.32E-01
7	6.58E-20	2.08E-10	7.39E-07	2.81E-04
8	1.20E-22	3.78E-13	6.47E-07	5.84E-07
9	2.18E-25	6.87E-16	5.75E-07	1.20E-09
10	3.96E-28	1.25E-18	5.17E-07	2.42E-12
11	7.21E-31	2.27E-21	4.70E-07	4.83E-15
12	1.31E-33	4.13E-24	4.31E-07	9.59E-18

Table 2: Number of expected full in-phase voltage addition events of all FM-IBOC stations that will occur in a 100 year period with PAPR=8 dB where n is the number of combined stations.

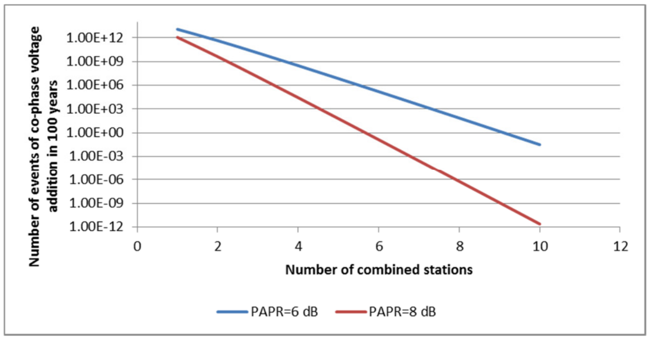

Figure 2: Number of expected full in-phase voltage addition events of all FM-IBOC stations that will occur in a 100 year period.

This analysis indicates that if one event within a 100 year period of co-phased voltage addition of all the combined stations is acceptable, approximately 9 IBOC stations must be included in the voltage breakdown and power handling calculations of all the RF components in the system when using a PAPR of 6 dB for all. If more than 9 IBOC stations are being combined, the voltage additions must be handled differently. Since the addition of the 10th station provides a total probability of exceedance that is less than one event in 100 years, the PAPR should be lowered in the voltage handling calculation for all stations in order to reflect the actual voltages that will produce the defined one event in 100 year criteria. The PAPR's that should be used for all the stations, independent of the actual PAPR's, in the total voltage calculations for a 1 in 100 year occurrence of exceedance can be derived using the same equations. Figure 3 provides this information. If for example, 8 IBOC stations are being combined, each with a PAPR greater than 6.5 dB, according to Figure 3, a PAPR of 6.5 dB should be used for each station in the total combined voltage calculation in order to normalize the peak voltage additions back to the 1 event in 100 year condition. This approach can be considered as applying a de-rating factor to the voltages for a large number of stations.

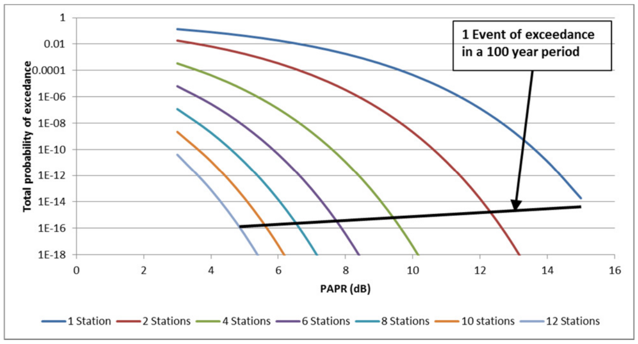

Figure 3: Recommended PAPR's to be used for total voltage handling calculations versus number of stations for a 1 in 100 probable occurrence of exceedance.

This statistical approach has one major drawback. It does not guarantee that an over voltage will not occur. If 100 years is specified for the average occurrence, there is no guarantee that the breakdown event will not occur in the first 5 minutes or two or three events will occur within 100 years. The odds are very small, but they are simply that, odds [1].

Peak Voltage and Power Rating

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 (8), where the .7 is a conservative number known as the DC to RF factor and is based on the fact that at RF the breakdown voltage has been experimentally measured at 22.8 kV/cm instead of the accepted value of 29 kV/cm[2].

$$V_{Peak\ RF} = .7xV_{DC} \quad (8)$$

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.

Effect of VSWR on Voltage Breakdown

The presence of mismatches at any point in the transmission system leads to the occurrence of standing waves that intensifies the electric field. The voltage along a transmission line can be expressed by equation (9).

$$|V_d| = |V_{inc}|[1 + |\Gamma|^2 + 2|\Gamma|cos(2\beta d - \theta_r)]^{1/2} \quad (9)$$

Where Γ is the reflection coefficient, $\beta=2\pi/\lambda$, and θ_r is the phase of the reflection coefficient. The maximum voltage that can occur is then given by:

$$|V_{max}| = |V_{inc}|(1 + |\Gamma|) \quad (10)$$

Noting that VSWR is related to the refection coefficient by:

$$|\Gamma| = \frac{VSWR - 1}{VSWR + 1} \quad (11)$$

Assuming the worst case scenario where the reflection from the mismatches are completely reflected back from the transmitter the maximum voltage can therefore be:

$$|V_{max}| = |V_{inc}|\frac{2\ x\ VSWR}{VSWR + 1} \quad (12)$$

More simply stated; the breakdown voltage magnification correction factor due to VSWR can be expressed as equation (13).

$$C_{VSWR} = \frac{2\ x\ VSWR}{VSWR + 1} \quad (13)$$

Safety Factors

Safety factors must be placed on the voltage breakdown and rated power level to ensure that environmental stresses and tolerances cannot stack up and cause failure. Not all components in the RF transmission system require the same safety factors. Since large portions of the radiating elements of antennas are typically exposed to weather, they require the highest safety factors whereas transmission lines and RF systems will only require a subset of the safety factors to be discussed. Paschen's Law, equation (14), can be used as a guide to help compile the safety factors necessary to ensure reliable operation.

$$V_B = \frac{apd}{ln(pd) + b} \quad (14)$$

This is a fundamental statement of behavior of voltage breakdown of gases. 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). This leads to the grouping of safety factors into four categories; pressure, medium, geometrical configuration and unknown effects.

Pressure Safety Factor

Pressure safety factors include temperature and altitude. Increasing the temperature and /or the altitude above sea level reduces gas density which is equivalent to lowering the Paschen pressure. A minimum voltage safety factor of 1.3 with respect to altitude and temperature is recommended for all environments [3].

Medium Safety Factor

The presence of impurities such as dust, moisture, rain, snow, ice, fog, humidity, salt atmosphere and corrosion lowers the air breakdown strength to approximately 40% of the dry air strength leading to a recommended design voltage safety factor of 2.5:1 [3],[4].

Geometrical Configuration Safety Factor

The electric field intensity near the inner conductor is inversely proportional to the radius of curvature of the surface and can be approximated by equation (15) where V is the applied voltage [5]. Refer to figure 4.

$$E_m \approx \frac{2V}{r\ ln\left(1 + \frac{4d}{r}\right)} \quad (15)$$

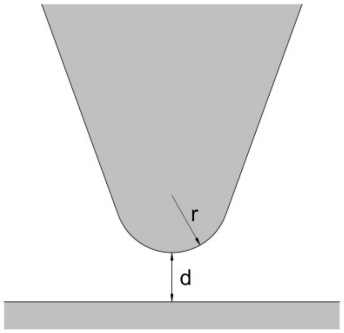

Figure 4

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. Allowing for a 5% variation in small gaps, a voltage safety factor of 1.1 is recommended for spacing tolerances including vibration, thermal expansion as well as surface and machining tolerances.

Unknown Effects

Unknown effects include such factors as accuracy of the DC Hi-Pot test which can vary up to 10% between locations and equipment, frequency, voltage tolerance variations, lightning induced transients, impedance variations and aging. Mostly based on historical data, a lumped recommended voltage safety factor to be used for miscellaneous unknowns is 1.5:1.

The resultant composite voltage safety factors that should be used for the design of RF systems, transmission lines and antennas are given Table 3.

	Pressure	Medium	Geometrical Configuration	Unknown Effects	**Composite S.F**
RF System	1.3	N/A	1.1	1.5	**2.1**
Transmission Line	1.3	N/A	N/A	1.5	**2**
Antenna	1.3	2.5	1.1	1.5	**5.4**

Table 3: Recommended voltage safety factors to be applied to the design of broadcast RF systems, transmission lines antennas.

Applied Voltage Calculation

The applied peak voltage between the inner and outer conductor for the analog FM is given by:

$$V_{p-analog} = \sqrt{2Z_0 P_{avg-analog}} \quad (16)$$

The PAPR plays a major role in determining the voltage peaks of the FM-IBOC signal. In order to scale the average power to account for the large peaks presented by the OFDM carriers, it must be multiplied by the PAPR.

$$V_{p-IBOC} = \sqrt{2Z_0 P_{avg-IBOC} PAPR} \quad (17)$$

When combining (n) multiple transmit signals assuming the worst case conservative approach where all the voltages are in co-phased addition, than the total applied voltage is simply the summation of each individual peak voltage. The voltage safety factor for a given component can then be determined by applying the VSWR correction factor and comparing this to the Hi-Pot test level given in equation (18).

$$SF = \frac{V_{peak\ RF}}{\left(\sum_1^n V_{p-analog} + \sum_1^n V_{p-IBOC}\right) C_{VSWR}} \quad (18)$$

It should be noted that from the previous analysis the summation of the IBOC voltages should use the recommended PAPR's given in Figure 3 for 100 year occurrence of breakdown so as to not over-size the components un-necessarily.

Consequence of -10dBc IBOC

A power increase to -10 dBc IBOC on multi-channel systems has a substantial impact on the design of every component, making certain they can handle the instantaneous voltage peaks. Considering as an example, 6" 50 ohm transmission line, the average power rating at FM frequencies and 0 psig is 178kW. If the goal would be to combine 9 FM stations, each with an analog average power of 10kW and using a PAPR of 6 dB, the relationship between the IBOC power level and the voltage safety factor can be plotted using equations 8,13,16,17 and 18 assuming the max VSWR=1.2:1 and the Hi-Pot level to be 40kV.

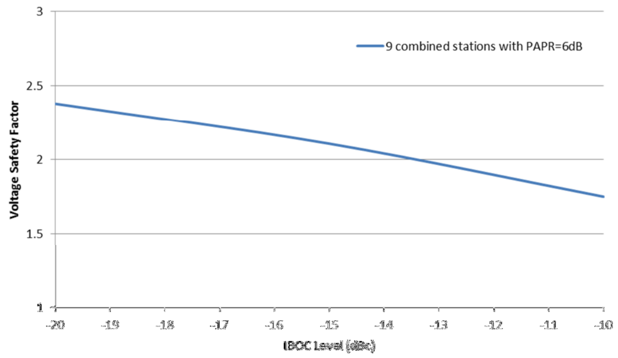

Figure 5: Voltage safety factor vs. IBOC power level for 6" 50 ohm transmission line assuming 9 combined stations each at 10 kW avg., max VSWR=1.2:1, and a test Hi-Pot level of 40kV.

Clearly the transmission line is not limited by the total average power of 90kW, but limited by the total peak voltage. Referring to Table 3, the recommended voltage safety factor is 2:1 for transmission line. In this example, a power increase from -20 dBc to -15 dBc would be acceptable, but not an increase to -10 dBc. In order to move all stations to -10 dBc, the line size would have to be increased to 8" 75 ohm in order to meet the recommended safety factor. Another useful application is to plot the maximum average power per station vs. the number of stations for a given safety factor, DC-Hi-Pot level and PAPR based on a 100 year occurrence. Referring to Figure 6, using a voltage safety factor of 2.1, a maximum VSWR of 1.2:1 and a DC Hi-Pot voltage of 40 kV which is associated with 6 1/8" 50 ohm transmission line, the maximum average power per station for a combined 6 stations is reduced approximately 50% when increasing the IBOC level of all the stations from -20 dBc to -10 dBc.

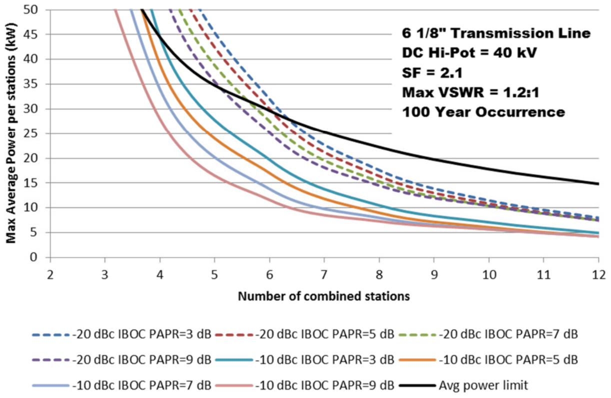

Figure 6: Maximum average power that can be applied to 6 1/8" 50 ohm transmission line vs. number of combined stations.

Note in Figure 6 the convergence of the curves for different PAPR's at the higher number of combined stations. This is due to de-rating the PAPR in accordance with the 1 in 100 year occurrence of the voltage addition exceedance discussed earlier. These are of course very basic examples, but the analysis can be adapted to any component in the system as well as individualizing the power levels and PAPR for each station.

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 much 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. Recommended voltage safety factors that should be applied to the design of broadcast RF systems, transmission lines and antennas are given, as well as the derivation of a VSWR corrections factor. Finally, a method to determine the peak voltage and power rating of each component in the system based on safety factors is established. Even though transmitter manufactures are striving for lower PAPR's, this attribute has little effect on RF component designers when combining a larger number of stations. This is due to the fact that the probability of co-phased voltage additions that exceed the PAPR decreases exponentially with the number of combined stations. When combining multiple stations and the probability of PAPR exceedance drops below the threshold value, (in the case of this paper, 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.

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