High Power RF Lightning Protection

by George M. Kauffman, PE, NexTek, Inc.

High RF power and lengthy antennas are critical ingredients for long range radio communication links. Exposure to lightning activity will impact these systems, depending upon site location and operational duration. This article will address some of the key parameters in designing and planning protection for applications above 1kW and up to 1 GHz. Traditionally, the challenge with these applications has been the low voltage and low transient capabilities of the protection components currently available. NexTek has solved this problem by increasing the RF power and transient current capabilities of a line of coaxial protectors.

Figure 1: Photo of NexTek High Power Protector

Figure 2: Photo of Gas Discharge Tube

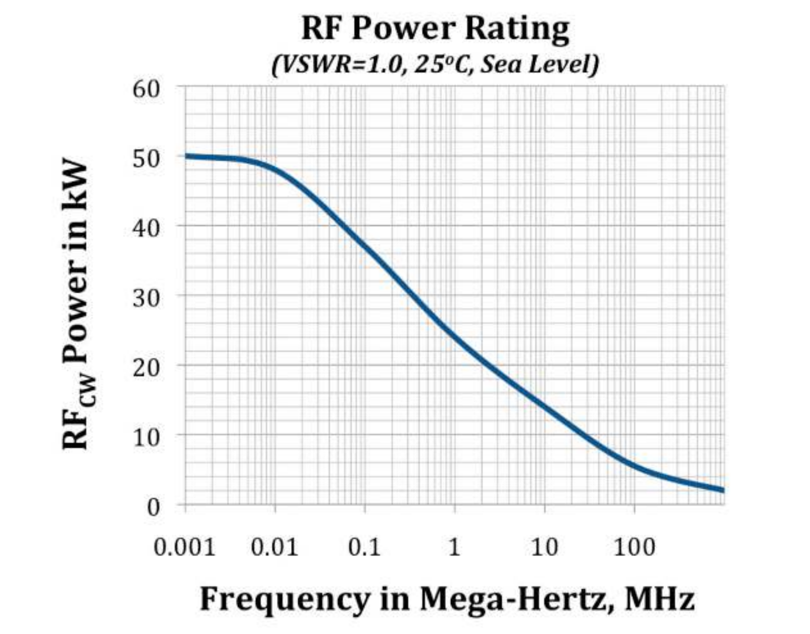

Figure 3: RF Power Rating of the PTR 7AF7AFxxK

Table 1: Skin Depth for Brass at Various Frequencies

Frequency	μm	.001"
10 kHz	1485	58.1
100 kHz	470	18.5
1 MHz	148	5.8
10 MHz	47.0	1.85
100 MHz	14.8	0.58
1 GHz	4.7	0.185
10 GHz	1.48	0.058

Protection Technology

The transmission line operation frequency and power level heavily influence the choice of protection technology. Lower frequency applications operating below about 400 MHz, including wide band or dc pass applications, usually use the gas discharge tube (GDT) as the primary transient current carrying component. These components switch from a non conductive state to a low resistance state at a predictable and consistent voltage range. These crowbar type devices are compact, have very high current ratings, and require a voltage impulse to initiate rapid triggering. They limit the application voltage and also the related RF power levels. At about 1GHz and above, the ideal protection technology is commonly a quarter wave stub or other direct shunt to ground. These shunting devices are generally band pass, without the ability to pass dc. Other more complex protectors are available, but these can have a more limited RF power capability.

A GDT consists of two end plates connected by a ceramic or glass tube as shown in Figure 2. The internal gap between the end plates is filled with a gas mixture that will break down and produce a short circuit arc at a predictable voltage.

The voltage, current and power of an ideal transmission line are related to each other through a perfect load impedance of 50Ω, with very familiar relationships. In a coaxial transmission line, the current flows on the outer surface of the inner conductor, and in the opposite direction on the inner surface of the outer conductor. Thus, the current density is the highest on the center conductor. The dissipation and temperature rise of the center conductor is usually a limiting factor in power capacity of a coaxial line.

Power Limitations

The power level of a coaxial transmission line, operating at a specified frequency, has two principal limiting parameters; thermal capability and voltage levels. The thermal capability is associated with the heat generation and the cooling efficiency of the structure. The voltage levels are primarily associated with the spacing between the center conductor and the shield, and the dielectric material within that spacing. Coaxial protectors generally inherit the limitations of the coaxial interface that is used.

The NexTek PTR7AF7AFxxK has been designed to be compatible with full power 7-16 DIN connectors as shown in Figure 1. The 7-16 DIN connectors can handle about 32 amperes of current at low frequency. This would equate to a basic thermal power rating of over $50kW_{CW}$ into 50Ω. 7-16 connectors are available with dielectric ratings of at least $1800V_{rms}$ or $2550V_{PEAK}$. This results in a voltage oriented basic rating of 80kW$_{CW}$ and 160kW$_{PEAK}$, both into 50Ω. A coaxial protector has additional restrictions on both the power dissipation and applied voltage, which will be explored in more detail.

Thermal Limitations

The heat generated by a protector is primarily associated with the current flow of the conductors. The skin depth effect at higher frequencies restricts the current to a thin surface layer of the conductors, which increases resistance and power dissipation. Table 1 shows the skin depth for brass at various frequencies. The effects are significant at 100kHz, while the current is further restricted to the thickness within typical metal plating thickness at frequencies above 1 GHz. The actual RF power rating is also heavily influenced by the mating connector limitations, as well as the design of the protector internals, including geometry and materials. The RF power rating for the NexTek dc pass high power 7-16 protector is shown in Figure 3. (Band pass protectors will generally tend to be a more symmetrical power limitation curve, with reduced power at lower frequencies as well.) *Caution, do not apply this curve to other protectors, or even other 7-16 protectors.* To attain this level of performance the NexTek protector has internal geometry equal to or exceeding the 7-16 connector. *Standard protectors on the market have reduced geometry internals, providing power capability more similar to N connectors.*

The center conductor will predominate in heat generation since it has a much smaller circumference than the inner surface of the outer conductor. Dielectric dissipation and component oriented losses can also be significant. The temperature rise of the protector will be a complicated relationship of the internal dissipation and internal thermal resistance, and the cooling surface area including mounting. The attaching cables may cause additional heat flow into the protector, based on the connector and cable design, materials, and geometry. The thermal limits are usually based on the rating of the polymer dielectric materials, and sometimes the temperature of the case if the connector is handled by operators.

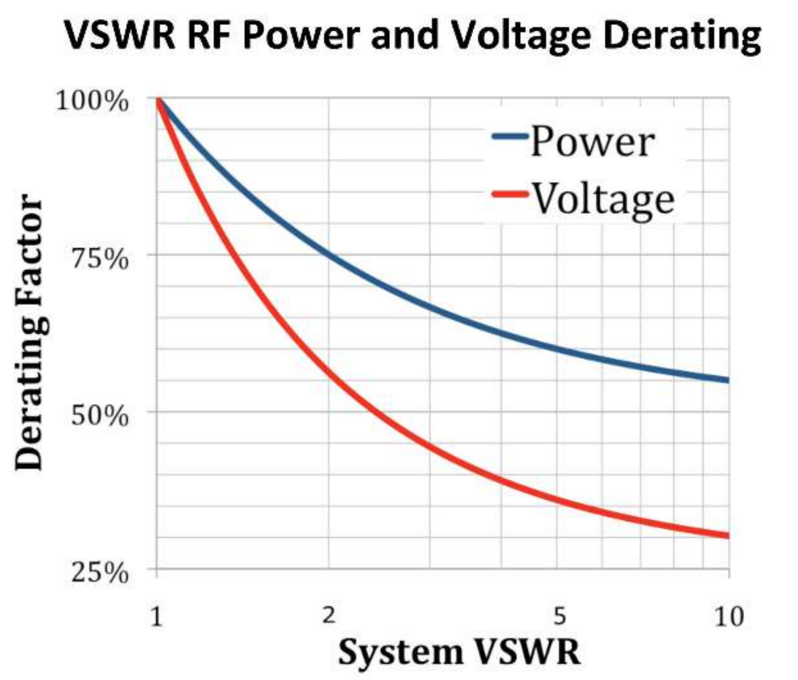

Figure 4: VSWR Derating Factor for RF Power and Voltage

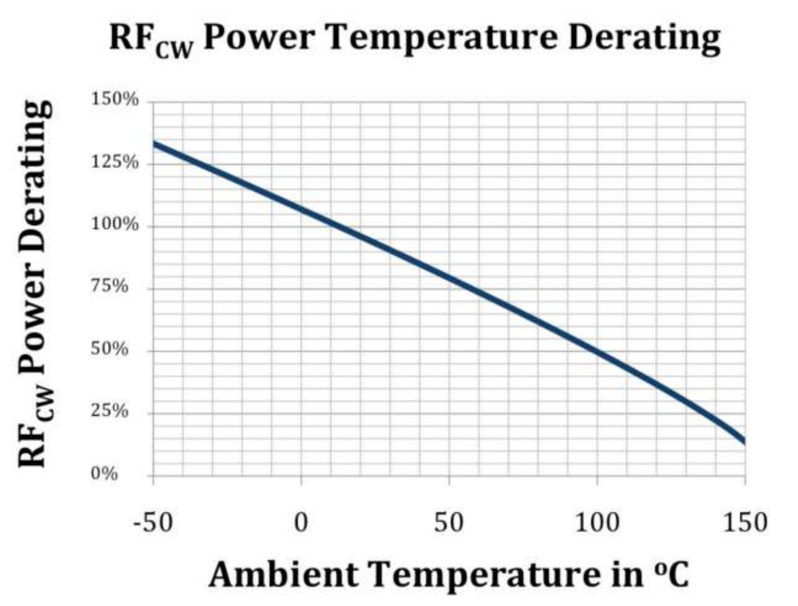

Figure 5: Thermal Derating of Power for Ambient Temperature

VSWR is a measure of reflected voltage and current, which will increase the power dissipation of the protector. An RF$_{CW}$ power derating factor, shown as the blue line in Figure 4, is usually the best way to handle this effect. The power derating factor decreases to 50% for the highest VSWR. The transmission line value of VSWR should be used here, including the antenna; not just the VSWR performance of the protector. The voltage VSWR derating will be discussed below.

The thermal power rating will be further affected by the ambient temperature. The typical temperature derating is shown in Figure 5; there are numerous factors which cause variation in this derating factor.

Air has lower density at altitude, and a reduced ability to cool the protector. The derating for operation at elevated locations is shown in Figure 6.

Since the maximum environmental temperature is usually lower at high altitudes, these two effects can compensate for each other, to a degree. It is better to make power estimates at low and high altitude and temperature separately. This curve varies widely at extremely high altitude, and should not be extrapolated to space applications, for this and other reasons.

Voltage Limitations

The peak voltage of a protector may be limited by a voltage limiting component. The NexTek PTR7AF7AFxxK has a variety of gas discharge tubes (GDT's) available. The operating peak voltage should be limited to 65% of the nominal rating of the protector component, to avoid unnecessary GDT triggering. The dielectric strength of the gap between the center and outer conductor is affected by altitude. The peak voltage rating for the NexTek 7/16 protector, as a function of altitude, is shown in Figure 7. *Caution, to not apply this curve to other protectors.* The power can be calculated from $P_{PEAK} = V_{PEAK}^2 / 50\Omega$. The horizontal voltage limits on Figure 7 at low altitude are associated with the standard Gas Discharge Tube voltages of 1.4 kV, 2.5kV and 3.5kV. The curved limit at higher altitudes is associated with the internal construction of the 7/16 connector. Other connector types have different high altitude limits.

The system VSWR causes elevated peak voltages in the transmission line. The Voltage derating factor is shown as the red line in Figure 4.

Special Caution Regarding Peak Voltage

The peak voltage of an RF$_{CW}$ power waveform is usually derived from the power and system impedance. This RF voltage is assumed to be sinusoidal, with a ratio of the peak to rms of 1.414. Be careful to recognize special cases where peak voltage will exceed this value. The most common examples of these applications are:

a. Use of multiple carriers or

combiners. To determine the composite peak voltage, the peak of each individual frequency should be summed; which will result in a peak voltage that exceeds the level associated with the sum of the RFW_{CW}.

b. The use of amplitude or phase modulation techniques, including pulsed output, can cause higher peak Voltage to rms.

c. On-off keying, intermittent or low duty cycle use can reduce the rms level for a given value of peak voltage.

d. The use of non-sinusoidal waveforms, particularly where there are periods of higher amplitude and lower amplitude energy.

Thermal Coordination of Transmission Line

The protector is only part of the high power story. Since the protector has two mating connectors within a short distance along the transmission line, attention to the mating connectors and cable is necessary since this combination has an enhanced effect on the temperature rise of that region of the transmission line. An ideal application would have the cable and connectors contributing to the protector cooling, as opposed to the reverse case.

In order to fully benefit from high power protector capability, consider the mating connectors and cable, and the mounting. The mating connector and cable must be rated for the power level and frequency. The cable dielectric material affects the temperature rise of the cable. An air dielectric cable will have the smallest dielectric gap between the center conductor and is usually easier to cool. A foam dielectric can be a better electrical and thermal insulator, and may also cause a dramatic temperature increase of the center conductor. Foam is great for peak voltage or power, but not as good for RFW_{CW} power. While solid dielectric may conduct heat better, the distance between the center conductor and the outer conductor is larger than it would be with air or foam dielectric. In general, cables with the largest center conductor have higher power capability.

The connector should have full pin geometry. Connectors with undersized male pins can result in higher dissipation. Some connectors use spring contacts to the copper surface of the cable center conductor. Electrical resistance and temperature rise can increase due to vibration and corrosion. High temperature solder is recommended for the most reliable center conductor connection.

The protector cooling can be augmented by the mounting arrangement. The mounting structure surface is an extension of the heat transfer surface of the protector. The best mounting for cooling is bulkhead fastening through a thick (6mm [1/4"]) metal panel. When mounting more than one high power protector, they should be spaced at least 30cm (12 inches) apart. Mounting protectors to a ground bar can provide cooling as well, depending upon the bracket and bar thickness. Mounting several protectors on a small common ground bus bar is not recommended. Grounding with a wire or flat strap will not appreciably help in cooling. Cooling can be augmented by connecting a large metal heat sink to the bulkhead provision of the protector, even if this is not needed for grounding or mounting.

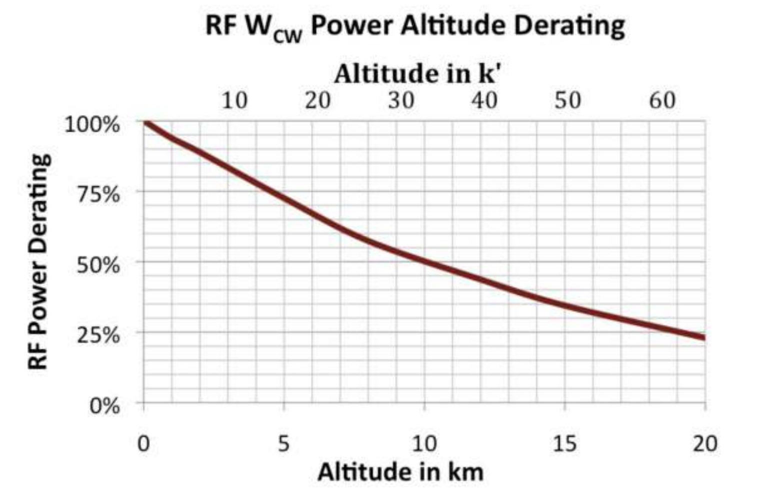

Figure 6: Altitude Power De rating for Altitude

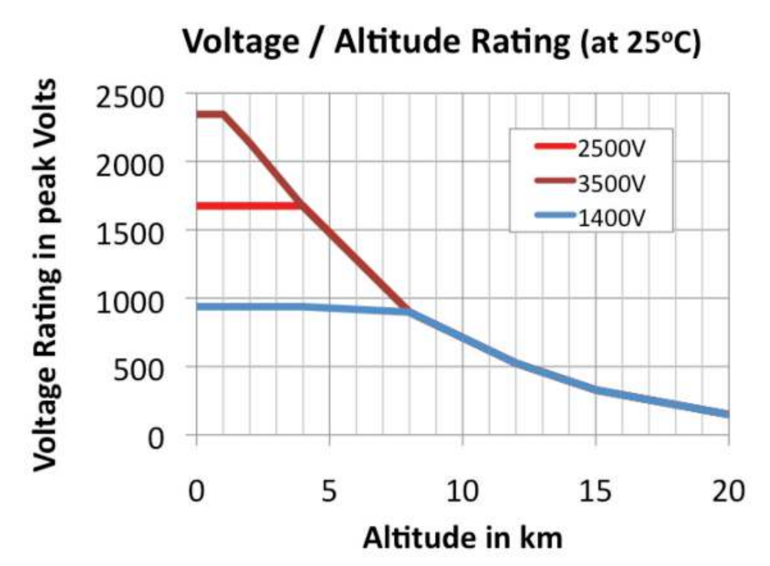

Figure 7: Altitude De rating of Voltage for NexTek PTR 7AF7AF XX K

Transient Pulse Lifetime

Pulse lifetime of a high power protector is usually limited by the rating of the GDT. The pulse rating most commonly used is the 8x20µs waveform. This waveform has a rise time of 8µs and a pulsewidth of 20µs. Lightning itself has a longer pulse width, and a peak current level rarely exceeding 100kA. Most applications will experience an attenuated current level with different rise time and pulsewidth. While there are several other waveforms that are in use, the 8x20µs is the most common and more than adequate to show the lifetime and response of a component or system to lightning related energy. It is convenient that the variety of lightning current pulses can be practically reduced to fundamental engineering terms for design analysis and test purposes. Commonly available GDTs rated over 1kW have pulse lifetime ratings of 10 pulses at 5 kA or one pulse at 10kA. While these levels of current are impressive in general electrical engineering usage, they are less than desired for coaxial protectors.

NexTek has perfected a technique of paralleling GDTs in a manner which shares the impulse current between them. Shown in Figure 8, this patented or patent pending technique has allowed an increase of the current rating to 10 pulses of 30kA, which generally leads the industry by a wide margin. Pulse life-time increases to 33 pulses at 10kA, instead of the more common 1 pulse; illustrating more than a decade of lifetime increase achieved with this new NexTek technology. The added benefit is that pulse lifetime is increased substantially at all current levels. No GDT failure would be expected for the vast majority of applications. At extreme risk sites, GDTs can be replaced, enabling the transmission line protection to renewed.

The largest non-lightning current factor in high RF power applications which could possibly affect the protector pulse lifetime is the system response to high VSWR. When a GDT is triggered, the arc makes a very low impedance short. As with any other short, this pro-

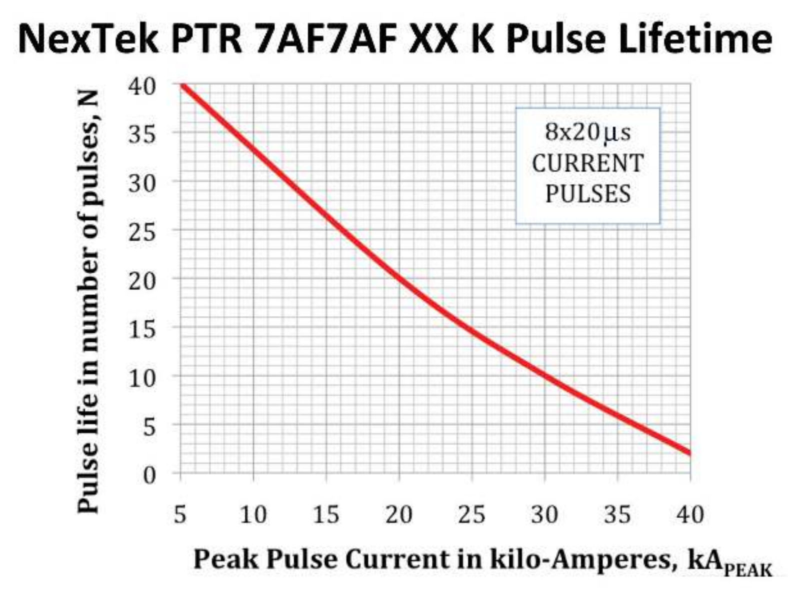

Figure 8: Pulse Lifetime of NexTek PTR7AF7AF XX K Protector

duces a short circuit current and high mismatch. NexTek's GDT system is fully capable of recovering and resealing with minimal aging of the GDT. In addition, most high power transmitters have high VSWR shut down or pause which will also force GDT off-commutation. The aging of GDTs is governed by the speed of the VSWR control circuit. For continuous transmission, the protector will last longer with a faster high VSWR detector and response.

Living on the Edge

The use of a transmission line at over 33% of the power or 50% of the voltage limits is considered high stress. High stress applications should have design or component qualification by testing. Some industry standard connectors are not able to survive high stress applications, even though they mate properly. Also, high stress systems might need manufacturing or field testing, since workmanship and tooling variations can cause performance variations. The guidelines given here include inherent assumptions; there is variation between and among various vendor's products, and a wide selection of coaxial cables to choose from. As the calculated stress climbs higher and higher, the need for testing increases. When you are closer to the edge, don't rely on models or calculations as a substitute for an actual trial. When dealing with high RF power, always observe appropriate safety practices.

Conclusion

Large format connectors such as the 7-16, can be used at substantially over 1 kW power levels, and provide unparalleled lifetimes. Gas discharge tube based protectors can provide robust protection for these transmission lines below 1GHz. The selection process is much more stringent than for typical applications, where there is considerable margin in most or all transmission line components. Careful attention to the electrical and environmental parameters will yield a reliable transmission line that is protected from the significant energy that threatens the system. Thorough modeling will also indicate if margins suggest that qualification testing is required.

About the Author

George M. Kauffman, PE, holds a BSME and MS in Engineering Management from the University of Massachusetts at Amherst. He leads NexTeks design and engineering team. George has extensive EMC and microwave design experience. He holds several patents in RF protection and related technology. He can be reached at engineering@nexteklightning.com

Example Design Calculations

Frequency: 440MHz band
RF power: Four $375W_{CW}$ channels or $1500W_{CW}$
VSWR: 2.0
Environment: 50ºC at Sea Level and 30ºC at 3km (10k')

The first step is to calculate each peak voltage or $(375x50\Omega)^{½}$ or $137V_{rms}$ or $193V_{peak}$. The actual peak voltage will be 4 x 193 or about $775V_{peak}$. The resulting peak power into 50Ω would be about 12kW.

Start the design with the middle voltage rated protector, or 2500V.

Parameter	Thermal Criteria		Voltage Criteria
Basic Rating	$50kW_{CW}$		$2.55kV_{PEAK}$ or $160kW_{PEAK}$
Altitude	Sea Level	3km	3km
Protector 400MHz Rating (3)	$3.0kW_{CW}$ At VSWR=1.0 and Sea Level		1640V (65% of 2.5kVnominal)
VSWR De rating (4)	75% at VSWR= 2.0		57%
Altitude De rating (6)	100% at SL	82% at 3km	1640V (no derating until 4km) (7)
Temperature De rating (5)	80% at 50ºC	90% at 30ºC	N/A
Power Rating	$1800W_{CW}$	$1660W_{CW}$	935V or 17.5kW (from $V^2/50\Omega$)
Requirements	$1500W_{CW}$		775V or 12kW
% Stress	83%	90%	83% Voltage/69% W_{CW}

3,4,5,6,7 References numbers indicate Figures used for calculations.

In this example voltage stress and the thermal stress are about the same. As long as input parameters do not significantly exceed their limits, 2.5 kV protector would be provide reliable long term service. There is limited room for growth. If we calculated with a 3500V protector, there would be ample peak voltage capacity, the thermal limit would be reached with very little RFCW power increase. To accommodate more transmission power the VSWR would have to be lowered, and/or the unit cooled exceptionally well.