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Power Capacity of Transmission Lines

(Case Study of Coaxial Cable)

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Abstract
The matrix of average power over frequency provided for each cable type is often used to evaluate the power capacity of transmission lines. There are two potential failure modes in cables also used to transmit high peak power. One is voltage breakdown; and the other is overheating. The major concern associated with application of peak power is breakdown due to high potential. In this paper, we have used coaxial cables as a case study to evaluate the power capacity of transmission lines. The study shows that the power capacity of transmission line also depends on the cable sizes and types and limited by voltage breakdown which occurs at a field strength of about $E_d = 3x10^6$V/m room temperature at sea level pressure. In addition, if there are reflections on the line or guide, the power capacity is further reduced. It is believed that the power capacity of the transmission line can be increased by pressurizing the line with air or an inert gas, or by using a dielectric.
Keywords: Impedance, Power Capacity, Transmission Line, Voltage Breakdown, Dielectric Strength.

1. Introduction

Power capacity of a transmission line means the power handling capacity of such a line. The power handling capacity of an air - filled transmission line or wave guide is however limited by voltage breakdown, which occurs at a field strength of about $E_d = 3x10^6$V/m for room temperature air at sea level pressure (Pozar, 2005). In an air filled coaxial line, the electric field varies as $E_p = V_o / (e \ln b/a)$, where ‘a’ and ‘b’ are the dimension which has a maximum at ρ = a. Thus the maximum voltage before breakdown is:

$$V_{max} = E_d \ln b/a, \text{ (peak-to-peak)} \quad (1)$$

and the maximum power capacity is then:

$$P_{max} = V^2_{max}/2Z_o = \pi a^2 E^2_d \ln b/a \quad (2)$$

As might be expected, this result shows that the power capacity can be increased by using a larger coaxial cable (large a, b with fixed b/a) for the same characteristic impedance). But propagation of higher order modes limits the maximum operating frequency for a given cable size. Thus, there is an upper limit on the power capacity of a coaxial line for a given maximum operating frequency, f_{max}, which can be shown to be given by:

$$P_{max} = 0.025/\eta_o (cE_d / f_{max})^2 = 5.8x10^{12} (E_d / f_{max})^2 \quad (3)$$

As an example, at 10 GHz, the maximum peak power capacity of any coaxial line with no higher order modes is about 520 KW. In an air – filled rectangular waveguide, the electric field varies as $E_y = E_o \sin(\pi \chi/a)$, which has a maximum value of E_o at $\chi = a$.

Thus the maximum power capacity before breakdown is:

$$P_{max} = abE_o^2/4Z_w = ab\, E_d^2/4Z_w \quad (4)$$

This shows that the power capacity increases with waveguide size. For most waveguides, b ≅ 2a. To avoid propagation of the TE_{20} mode, we must have: $a < c/f_{max}$, where f_{max} is the maximum operating frequency. Then the maximum power capacity of the guide can be shown to be:

$$P_{max} = 0.11/ \eta_o(c\, E_d/ f_{max})^2 = 2.6x10^{13}(E_d / f_{max}) \quad (5)$$

As an example, at 10 GHz the maximum peak power capacity of a rectangular waveguide operating in the TE_{10} mode is about 2300 KW, which is considerably higher than the power capacity of a coaxial cable at the same frequency. It is good engineering practice to provide a safety factor. Hence, we should avoid transmitting peak power quantities. It is always good to avoid the two extremes. In addition, if there are reflections on the line or guide, the power capacity is further reduced. It is believed that the power capacity of the transmission line can be increased by pressurizing the line with air or an inert gas, or by using a dielectric (Pozar, 2005). The dielectric strength (E_d) of most dielectrics is greater than that of air, but the power capacity may be primarily limited by the heating of the dielectric due to ohmic loss (Pozar, 2005).

1.1 Transmission Lines And Their Characteristics

Transmission lines are interconnections that convey electromagnetic energy from one point to another. The energy may be for light, heat, mechanical work, or information - speech, music, pictures, and data (Tewari , 2005). Transmission lines may be individual or multiple wires, or specially constructed cables. It may also be special structures, such as waveguides for microwave signals, or fiber optic cables for light wave transmissions. In communication systems, there are eight principal types of transmission lines or special structures. They include: (Kraus and Fleisch , 1999)

- Single wire
- Twisted pair
- Two-wire shielded
- Strip
- Micro strip
- Coaxial cable
- Waveguides
- Fiber - Optic cable

The micro strip transmission line is the most widely used line, with applications in integrated circuits and circuit boards. Although much more convenient to use than coaxial cable, it is not shielded and has a fringing field (Tewari, 2005).

In this work, emphasis is more on coaxial cable because of its inherent qualities. Coaxial cable was invented to provide a transmission line that had relatively low loss per foot, excellent shielding from outside signals, durability for hard wear, and pliability for all variety of applications at wide range of frequencies. Coaxial cables have higher losses than open wire lines but are not influenced by nearby objects and are easy to install. Coaxial cables differ in sizes and in their line losses. The losses increase with frequency (Kraus and Fleisch , 1999). Normally, it is expected that the larger the lines physically, the lower the losses that are encountered. The losses are given in decibels (dB) per 100 feet (about 30 m) and usually are specified as a function of frequency. At VHF and UHF frequencies, special coax transmission lines, called hard lines, are used. These coaxial cables have a large inner conductor and a hard outer conductor. Such lines are often used in commercial operations with large antenna towers where long coaxial runs are required. Hard lines have very-low loss per 100 feet(30m) compared to the RG type and can operate up to frequencies of about 1500 MHz. The power capacity of transmission line decreases with frequency rise (Harbour, 2011).

1.2 Transmission Line Theory

The electrical characteristics of a two - wire transmission line depend primarily on the construction of the line. The two - wire line acts like a long capacitor. The change of its capacitive reactance is noticeable as the frequency applied to it is changed. Since the long conductors have a magnetic field about them when electrical energy is being passed through them, they also exhibit the properties of inductance. The values of inductance and capacitance presented depend on the various physical factors: the type of line used the dielectric in the line, and the length of the line. The effect of the inductive and capacitive reactance of the line depends on the frequency applied. Each type of two - wire transmission line also has a conductance value. This conductance value represents the value of the current flow that may be expected through the insulation. If the line is uniform (all values equal at each unit length), then one small section of the line may represent several feet (Tewari, 2005).

Transmission line constants (resistance, capacitance, inductance and conductance) are spread along the entire length of the transmission line and cannot be distinguished separately. The amount of inductance, capacitance and resistance depends on the length of the line, the size of the conducting wire, the spacing between the wires, and the dielectric (air or insulating medium) between the wires. These primary constants are normally referred to as distributed parameters (Kraus and Fleisch , 1999). Apart from the basic function of conveying signals power, usually at high frequencies, transmission lines and waveguides also provide other important functions, which include:

- Impedance matching
- Impedance transformation
- Mode excitation

- Filtering
- Construction of distributed network components.

1.3 Characteristic Impedance Of Transmission Line

Each transmission line is designed to have particular characteristic impedance, Z_o. Its value is based on the physical size of the conductors used, the separation distance of the conductors, and the dielectric of the insulation separating the conductors. It is very important to understand that the characteristic impedance is the same everywhere along the length of the transmission line. The characteristic impedance appears as a resistance for the lossless line. The characteristic impedance of a transmission line is so important for the efficient transfer of energy.

1.4 Power Loss Of A Transmission Line

Some of the power that is fed into a transmission line is lost because of its resistance. This effect is called ohmic or resistive loss. At high frequencies, another effect called dielectric loss becomes significant, adding to the losses caused by resistance. Dielectric loss is caused when the insulating material inside the transmission line absorbs energy from the alternating electric field and converts it to heat. The total loss of power in a transmission line is often specified in decibels per meter (dB/m), and usually depends on the frequency of the signal. The manufacturer often supplies a chart showing the loss in dB/m at a range of frequencies. A loss of 3dB corresponds approximately to a halving of the power. The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line. For a short line, the heating of conductors due to line losses sets a “thermal” limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by over-heating. For intermediate-length lines on the order of 100km (60 miles), the limit is set by the voltage drop in the line. For longer AC lines, system stability sets the limit to the power that can be transferred. Very approximately, the allowable product of line length and maximum load is proportional to the square of the system voltage.

2. Power Capacity Of Transmission Line Calculation

In this section, we are to calculate the power capacity of transmission lines using the available parameters in order to investigate the theoretical statements above.

2.1 Dielectric Strength

The field intensity **E** in a dielectric cannot be increased indefinitely. If a certain value is exceed, sparking occurs and the dielectric is said to break down. The maximum field intensity that a dielectric can sustain without break down is called its dielectric strength (Tewari, 2005). The dielectric strengths of some dielectric materials are listed in Table 2 below. The dielectric strengths are for a uniform field, and the materials are arranged in order of increasing strength (Tewari, 2005).

3. Case Study

Here, we are using two types of coaxial cables to carry out our analysis. We are trying to investigate the power handling capacities of these cables (coaxial). The outcome will warrant us to make a useful statement(s) that could be further investigated.

3.1 Mechanical Elements Of Coaxial Cable

An example of a flexible, solid dielectric coaxial line is shown in figure 1. Polyethylene dielectric is the usual choice for two - radio cables. It is the most economical and has both low loss and long life. Teflon is also sometimes used as insulation for high power service since it is capable of operating at substantially higher temperatures than polyethylene. It is typically much more expensive than polyethylene.

3.2 Power Handling Capability

The power handling capability of coaxial cable or line is limited by the ambient temperature (the temperature of the air around the outside of the cable), the cable’s temperature at average power, and by conductor spacing and dielectric strength at peak power. Normally, average power is the main factor. Power loss also increases with frequency, but average power rating decreases with increase in frequency [RF].

CASE 1: COAXIAL CABLE (RG-Type, Cheminax; Impedance = 50 ohms)

Using equations (1) and (3), V_{max} and P_{max} may be calculated as follows as shown in table 1

Where $V_{max} = E_d \ln b/a$, (peak –to-peak), and $P_{max} = 0.025/\eta_o(cE_d / f_{max})^2$.

Another sample of coaxial cable was considered and in the same way P_{max} and V_{max} were calculated. The values obtained were shown in table 3.

CASE 2: RG- Coaxial cables.
RG is a symbol used to designate coaxial cables that are made to Government Specifications. The letter **R** stands for radio and letter **G** for government. This is shown in table 4.

4. Conclusion

A close look at the results show variations in maximum power, P_{max} and maximum voltage, V_{max} obtained. This is actually in line with the expected results from theoretical predictions. The results also show that power loss increases with frequency rise and it is also in line with the theoretical predictions.

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Table 1: Coax Specifications at Two Different Frequencies (Kraus and Fleisch , 1999)

Coax Type	RG-6	RG-59	RG-58U	RG-8X	RG-213	RG-8U	Hard-line
Loss at 100 MHz	2.3dB	2.9dB	4.3 dB	3.7 dB	1.9 dB	1.9 dB	0.5 dB
Loss at 400 MHz	4.7dB	5.9dB	9.4 dB	8.0 dB	4.1 B	4.5 dB	1.5 dB

Table 2: Dielectric Strengths

Material	Dielectric Strength in MVm^{-1}
Air (atmospheric pressure)	3
Oil (mineral)	15
Paper (impregnated)	15
Polystyrene	20
Rubber (hard)	21
Bakelite	25
Paraffin	30

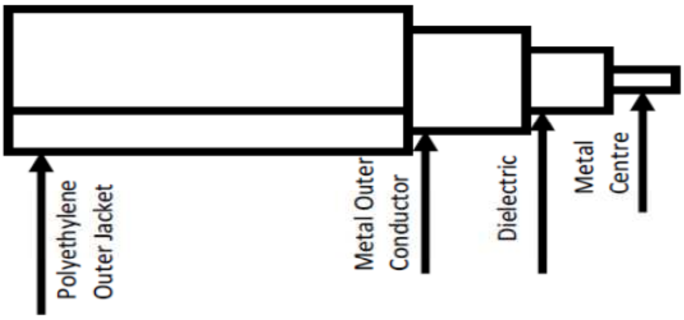

Figure 1: Showing the mechanical elements of coaxial cable

Table 3: RG-Type, Cheminax

Part	Outer Diameter(b)	Inner Diameter (a)	P_{max} (KW)	V_{max} (V/m)
5012A3311-0	8.64mm	2.24mm	492	9,071
5012A3811-0	8.55mm	2.24mm	448	9,001
5012E1339-0	10.24mm	2.26mm	560	10,244
5018A1311-0	4.7mm	1.27mm	153	4,985
5019D3318-0	4.45mm	0.91mm	95.4	4,333
5020A1311-0	3.76mm	1.02mm	98.5	3,992
5020A1811-0	3.81mm	1.02mm	99.5	4,032
5020A3311-0	4.29mm	1.02mm	108	4,395
5021D1331-0	4.77mm	0.89mm	96.5	4,443
5024A1331-0	2.67mm	0.64mm	42.4	2,742

Table 4: RG- Coaxial Cables

MATERIAL	P_{max}(KW)	V_{max}(V/m)
RG-174/u	8.986	0.1485
RG-178	1.570	0.7723
RG-179/u	82.952	2.142
RG-316/u	89.857	2.475
RG-58/u	332.612	4.739
RG-8/x	606.492	5.332
RG-59/u	496.942	5.550
RG-223/u	298.306	5.954
RG-213/u	1347.706	7.734
RG-11/u	1420.09	8.150