

Figure 11.8 Current-voltage diagram or power-indicator diagram of electric alternating currents

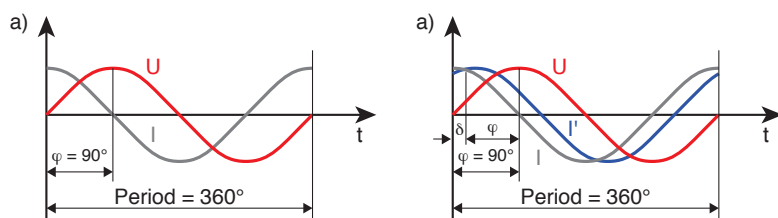


Figure 11.9 Current and voltage in a condenser. $I \equiv$ current, $U \equiv$ voltage, $t \equiv$ time a) Without dielectric losses (ideal condition), current and voltage are displaced by the phase angle $\varphi = 90^\circ$ or $\pi/2$; b) With dielectric loss, the current curve I' is delayed by the loss angle δ

If the condenser has losses, when $\tan \delta > 0$, a resistive current I_r is formed leading to a heating energy rate in the dielectric of

$$E_h = \frac{1}{2} U I_{eff} \tan \delta \tag{11.27}$$

where I_{eff} represents the total current or the magnitude of the vector in Fig. 11.8. Using Eq. 11.25 for capacitance leads to

$$C^* = C' - \frac{1}{R\omega} = C' - iC'' \tag{11.28}$$

where C^* is the complex capacitance, with C' as the real component defined by

$$C' = \epsilon_0 \epsilon_r' \frac{A}{d} \tag{11.29}$$

and C'' as the imaginary component described by

$$C'' = \frac{1}{R\omega} = \epsilon_0 \epsilon_r'' \frac{A}{d} \tag{11.30}$$

Using the relationship in Eq. 11.5 we can write

$$C^* = C_0 (\epsilon_r' - i\epsilon_r'') = C_0 \epsilon_r^* \tag{11.31}$$

where ϵ_r^* is called the *complex dielectric coefficient*. According to Eqs. 11.25 and 11.31, the phase angle difference or *dielectric dissipation factor* can be defined by

$$\tan \delta = \frac{I_r}{I_c} = \frac{\epsilon_r''}{\epsilon_r'} \quad (11.32)$$

If we furthermore consider that electric conductivity is determined by

$$\sigma = \frac{1}{R} \frac{d}{A} \quad (11.33)$$

then the imaginary component of the complex dielectric coefficient can be rewritten as

$$\epsilon_r'' = \frac{\sigma}{\omega \epsilon_0} = \epsilon_r' \tan \delta \quad (11.34)$$

Typical ranges for the dielectric dissipation factor of various polymer groups are shown in Table 11.2. Figures 11.10 [1] and 11.11 [1] present the dissipation factor $\tan \delta$ as a function of temperature and frequency, respectively.

Table 11.2 Dielectric Dissipation Factor ($\tan \delta$) for Various Polymers

Material	$\tan \delta$
Non-polar polymers (PS, PE, PTFE)	< 0.0005
Polar polymers (PVC and others)	0.001 - 0.02
Thermoset resins filled with glass, paper, cellulose	0.02 - 0.5

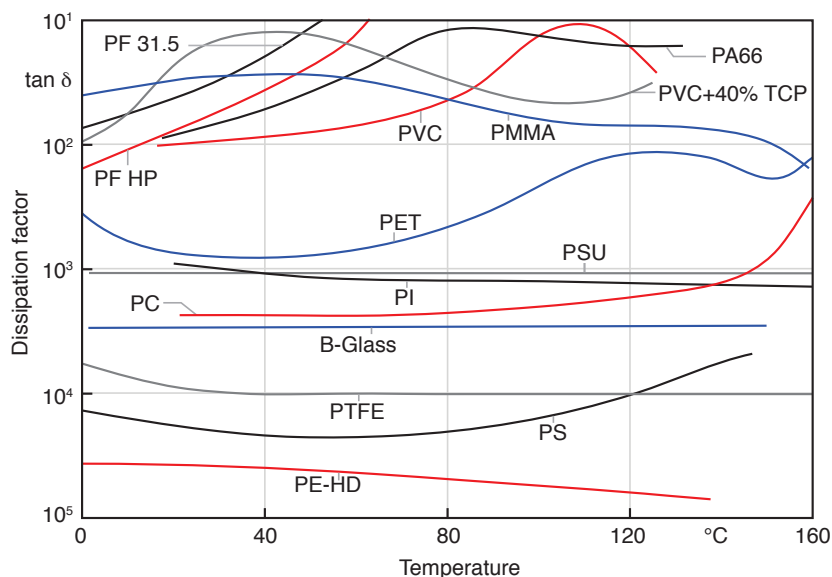


Figure 11.10 Dielectric dissipation factor as a function of temperature for various polymers

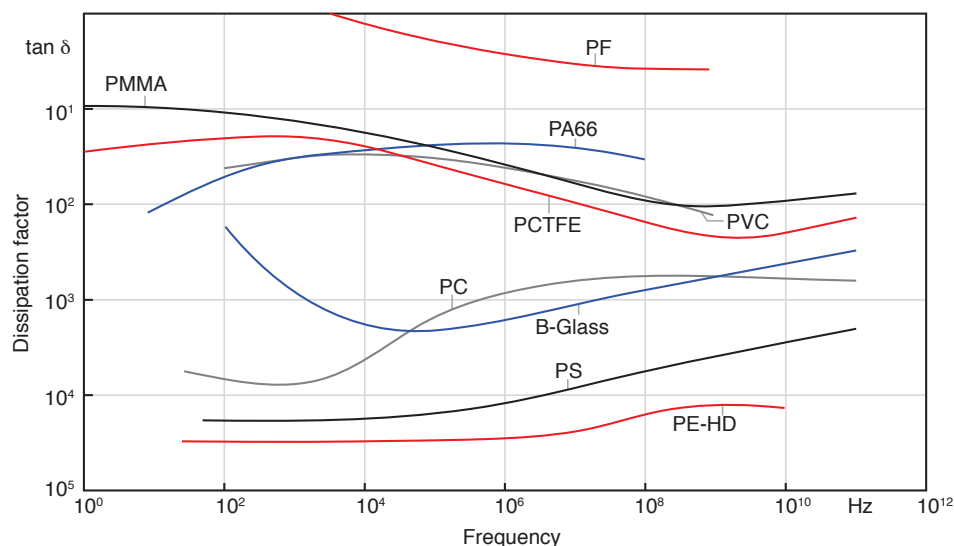


Figure 11.11 Dielectric dissipation factor as a function of frequency for various polymers

11.1.4 Implications of Electrical and Thermal Loss in a Dielectric

The electric losses through wire insulation running high frequency currents must be kept as small as possible. Insulators are encountered in transmission lines or in high-frequency fields such as the housings of radar antennas. Hence, we would select materials that exhibit low electrical losses for these types of applications.

On the other hand, in some cases we want to generate heat at high frequencies. Heat sealing of polar polymers at high frequencies is an important technique used in the manufacturing of soft PVC sheets, such as the ones encountered in automobile vinyl seat covers.

To assess whether a material is suitable for either application the loss properties of the material must be determined and the actual electrical loss calculated. To do this, we can rewrite Eq. 11.27 as

$$E_h = U^2 \omega C \tan \delta \quad (11.35)$$

or as

$$E_h = 2\pi f U^2 d^2 \epsilon_0 \epsilon_r' \tan \delta C_0 \quad (11.36)$$

The factor that is dependent on the material and indicates the loss is the *loss factor* $\epsilon_r' \tan \delta$, called ϵ_r'' in Eq. 11.34. As a rule, the following should be used:

$\epsilon_r' \tan \delta < 10^{-3}$ for high-frequency insulation applications, and

$\epsilon_r' \tan \delta > 10^{-2}$ for heating applications.

In fact, polyethylene and polystyrene are perfectly suitable as insulators in high-frequency applications. To measure the necessary properties of the dielectric, the standard DIN 53 483 and ASTM D 150 tests are recommended.

■ 11.2 Electric Conductivity

11.2.1 Electric Resistance

The current flow resistance, R , in a plate-shaped sample in a direct voltage field is defined by Ohm's law as

$$R = \frac{U}{I} \quad (11.37)$$

or by

$$R = \frac{1}{\sigma} \frac{d}{A} \quad (11.38)$$

where σ is known as the conductivity and d and A are the sample's thickness and surface area, respectively. The resistance is often described as the inverse of the conductance, G ,

$$R = \frac{1}{G} \quad (11.39)$$

and the conductivity as the inverse of the specific resistance, ρ ,

$$\sigma = \frac{1}{\rho} \quad (11.40)$$

The simple relationship found in Eq. 11.37–39 is seldom encountered because the voltage, U , is rarely steady and usually varies in cyclic fashion between 10^{-1} to 10^{11} Hz [3].

Current flow resistance is called *volume conductivity* and is measured one minute after direct voltage has been applied using the DIN 53 482 standard test. The time definition is necessary, because the resistance decreases with polarization. For some polymers we still do not know the final values of resistance. However, this has no practical impact, because we only need relative values for comparison. Figure 11.12 compares the specific resistance, ρ , of various polymers and shows its dependence on temperature. Here, we can see that similar to other polymer properties, such as the relaxation modulus, the specific resistance not only decreases with time but also with temperature.

The surface of polymer parts often shows different electric direct-current resistance values than their volume. The main cause of this phenomenon is surface contamination (e.g., dust and moisture). We therefore have to measure the surface

resistance using a different technique. One common test is DIN 53 482, which uses a contacting sample. Another test often used to measure surface resistance is DIN 53 480. With this technique, the surface resistance is tested between electrodes placed on the surface. During the test, a saline solution is dripped on the electrodes causing the surface to become conductive, thus heating up the surface and causing the water to evaporate. This leads not only to an increased artificial contamination but also to the decomposition of the polymer surface. If during this process conductive derivatives such as carbon form, the conductivity quickly increases to eventually create a short circuit. Polymers that develop only small traces of conductive derivatives are considered resistant. Such polymers are polyethylene, fluoropolymers, and melamines.

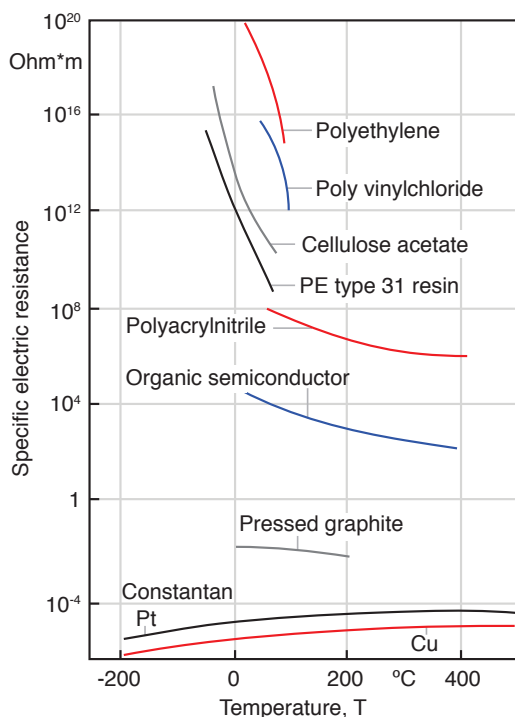


Figure 11.12 Specific electric resistance of polymers and metals as a function of temperature

11.2.2 Physical Causes of Volume Conductivity

Polymers with a homopolar atomic bond, which leads to pairing of electrons, do not have free electrons and are not considered to be conductive. Conductive polymers in contrast, allow for movement of electrons along the molecular cluster, because

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