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Inductive and Capacitive Voltage Measurement

20.1 Introduction

Capacitive and inductive voltage sensors are mainly utilized in low-frequency electric measurements. In this chapter, the capacitive and inductive measurement with large voltage ranges, from $10^{-10}$ to $10^7$ V, has been discussed. The associated voltage waveforms can be periodic or impulsive. In periodic waveforms, it is often important to measure the spectrum and the subharmonic components, which can vary depending on the position of the measuring devices within the same network. In impulsive measurements, obtaining the maximum voltage values, the pulse lengths, etc., is preferred.

20.2 Capacitive Sensors

The voltage to be measured can be reduced by means of capacitive dividers (Figure 20.1). Capacitive dividers are affected by temperature and frequency and therefore are not important, at least in Europe. Capacitive sensors detect voltage by different methods:

1. Electrostatic force (or torque)
2. Kerr or Pockels effect
3. Josephson effect
4. Transparency through a liquid-crystal device
5. Change in refractive index of the fiber or in light pipe

The relations that rule the listed capacitive voltage sensors are reported in the succeeding text. The force between two electrodes is (Figure 20.2)

$$ F = \varepsilon_0 \frac{S}{d} (V_1 - V_2)^2 $$  \hspace{1cm} (20.1)
Electrical Variables

\[ \epsilon_0 \text{ is the dielectric constant} \]
\[ S \text{ is the area of the electrode} \]
\[ d \text{ is the distance} \]
\[ V_1, V_2 \text{ are the potentials of the electrodes} \]

The torque between electrostatic voltmeter quadrants (Figure 20.3) is given by

\[ T = \frac{1}{2} \frac{\partial C}{\partial \theta} (V_1 - V_2)^2 \quad (20.2) \]

where
\[ C \text{ is the capacitance} \]
\[ \theta \text{ is the angle between electrodes} \]

To get the torque from the rate of change (derivative) of electrostatic energy versus the angle is easy. Obtaining the torque by mapping the electric field is difficult and requires long and complex field computing.

2. The rotation of the polarization plane of a light beam passing through a KDP crystal under the influence of an electric field (Pockels effect) is expressed by (Figure 20.4)

\[ \theta = k_p l (V_1 - V_2) \quad (20.3) \]

where
\[ k_p \text{ is the electro-optic constant} \]
\[ l \text{ is the length of crystal} \]

One obtains a rotation of $\pi/2$ by applying a voltage of the order of 1 kV to a KDP crystal of a few centimeters in length.

\[ \text{FIGURE 20.1} \quad \text{Schematic arrangement of a capacitive divider.} \]

\[ \text{FIGURE 20.2} \quad \text{Force between two electrodes with an applied voltage.} \]
If a light beam passes through a light pipe that performs the Kerr effect, one observes a quadratic dependence of the rotation versus $V$:

$$\theta = kE^2 = k'V^2$$ (20.4)

3. The Josephson effect consists of translation of a voltage into a periodical signal of a certain frequency, carried out by a special capacitive sensor. There is an array of $N$ layers of Josephson superconducting junctions; the frequency of emitted signal, when a voltage $V$ is applied, is given by

$$\nu = \frac{2eV}{Nh}$$ (20.5)
4. The transparency of a liquid-crystal device depends on the difference of potential applied. There are liquid-crystal devices working in transmission or in reflection. A change in transparency is obtained when a difference of potential of a few volts is applied. 

5. The change in refractive index due to the presence of an electric field can be detected by
   a. Interferometric methods (where the velocity of light is equal to c/\(n\))
   b. Change in light intensity in a beam passing through an optical waveguide device like Li-Nb (Figure 20.5)

By means of method 1, many kinds of instruments (voltmeters) can be realized. Methods 2 through 5 are used in research laboratories, but they are not yet used in industrial measurements.

### 20.3 Inductive Sensors

#### 20.3.1 Voltage Transformers

Voltage transformers (VTs) have two different tasks:

- Reduction in voltage values for meeting the range of normal measuring instruments or protection relays
- Insulation of the measuring circuit from power circuits (necessary when voltage values are over 600 V)

VTs are composed of two windings—one primary and one secondary winding. The primary winding must be connected to power circuits; the secondary to measuring or protection circuits. Electrically, these two windings are insulated but are connected magnetically by the core.

One can define the following

\[
\text{Nominal ratio} = K_n = \frac{V_{\text{in}}}{V_{\text{sec}}} 
\]

as the ratio between the magnitude of primary and secondary rated voltages.

\[
\text{Actual ratio} = K = \frac{V_1}{V_2} 
\]

as the ratio between the magnitudes of primary and secondary actual voltages.
**Burden** is the value of the apparent power (normally at \( \cos \varphi = 0.8 \)) that can be provided on the secondary circuit (instruments plus connecting cables).

Burden limits the maximum value of secondary current and then the minimum value of impedance of the secondary circuit is

\[
Z_{\text{min}} = \frac{V_{2n}^2}{A_n}
\]

(20.8)

where \( A_n \) is the VT burden.

For example, if \( A_n = 25 \text{ VA} \) and \( V_{2n} = 100 \text{ V} \), one obtains

\[
Z_{\text{min}} = \frac{100}{0.25} = 400 \text{ W}
\]

(20.9)

There are two kinds of errors:

1. Ratio error = 
\[
h_{\text{ratio}} = \frac{K_n - K}{K}
\]

(20.10)

2. Angle error = the phase displacement between the primary voltage and the secondary voltage (positive if the primary voltage lags the secondary one).

VTs are subdivided into accuracy classes related to the limits in ratio and angle error (according to CEI and IEC normative classes 0.1, 0.2, 0.5, 1, 3; see Table 20.1). To choose the VT needed, the following technical data must be followed:

- Primary and secondary voltage (rated transformation ratio). Normally, the secondary value is 100 V.
- Accuracy class and rated burden in VA: for example, cl. 0.5 and \( A_n = 10 \text{ VA} \).
- Rated working voltage and frequency.
- Insulation voltage.
- Voltage factor: the ratio between maximum operating voltage permitted and the rated voltage. The standard voltage factor is 1.2 \( V_n \) (i.e., the actual primary voltage) for an unlimited period of time (with VT connected with phases) and is 1.9 \( V_n \) for a period of 8 h for VT connected between phase and neutral.
- Thermal power is the maximum burden withstood by VT (errors excluded).

### Table 20.1  Angle and Ratio Error Limit Table Accepted by CEI and IEC Standards

<table>
<thead>
<tr>
<th>Class</th>
<th>Percentage Voltage Error (±)</th>
<th>Phase Displacement Minutes (±)</th>
<th>Centiradians (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>5</td>
<td>0.15</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>20</td>
<td>0.6</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>40</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3P</td>
<td>3</td>
<td>120</td>
<td>3.5</td>
</tr>
<tr>
<td>6P</td>
<td>6</td>
<td>240</td>
<td>7</td>
</tr>
</tbody>
</table>

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For extremely high voltage values, both capacitive dividers and VTs are normally used, as shown in Figure 20.6. The capacitive impedance must compensate for the effect of the transformer’s internal inductive impedance at the working frequency.

20.3.2 Other Methods

The ac voltage inductive sensors act by interaction between a magnetic field (by an electromagnet excited by voltage to be measured) and the eddy current induced in an electroconductive disk, producing a force or a torque. This can be achieved by the scheme shown in Figure 20.7. The weight of many parts of the indicator can be some tens of grams. The power absorbed is on the order of a few watts. The precision is not high, but it is possible to get these sensors or instruments as they are similar to the widely produced induction energy meters. They are quite robust and are priced between $50 and $100, but they are not widely used. The relation between torque and voltage is quadratic:

\[ T = k_i V^2 \]  

(20.11)

The proportionality factor \( k_i \) depends on magnet characteristics and disk geometry.

GEC, Landis & Gyr, ABB, Schlumberger, etc., are the major companies that furnish components and instruments measuring voltage by inductive and capacitive sensors.
Defining Terms

CEI: Comitato Elettrotecnico Italiano
IEC: International Electric Committee
KDP: potassium dihydrogen phosphate
Li-Nb: (LiNbO₃) lithium niobate

Further Information