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ABSTRACT

When a dc amplifier with capacitive feedback is used as an integrator
from a voltage source, certain errors are introduced that are not present
when a current source such as an ionization chamber is used.

The necessary conditions for this kind of operation and the errors
produced are discussed. These errors are produced because a return path
to ground is provided by the source.
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It is frequently necessary and desirable in computer, control, or measuring devices to use a 100% inverse feedback dc amplifier to integrate a voltage whose source is connected to ground. It is the purpose of this article to indicate the errors produced in this type of system due to the source impedance and other factors not found when a current source is used. Such a system is shown in Fig. 1.

The symbols used below are as follows:

- $A$, the dc amplifier gain.
- $e_s$, the instantaneous value of the source voltage.
- $E_s$, the average source voltage over one period of integration.
- $e_i$, the instantaneous voltage at the input of the dc amplifier relative to the input voltage when the unit is zeroed.
- $e_c$, the potential difference between the input to the amplifier and ground when the unit is zeroed. There is always some small error because it is impossible to zero exactly, and the zero point may also drift. This is given the polarity as measured on the meter.
- $e_c$, the voltage on the capacitor.
- $R$, the internal resistance of the source plus any added series resistance.
- $C$, the value of the feedback capacitor.
- $e_o$, the voltage at the output of the amplifier as measured with the meter connected as shown (it is equal to $Ae_i$ although in opposite polarity to the voltage as measured with respect to ground. The polarity of the amplifier output is opposite to the input polarity).
- $E_o$, the output voltage at the end of the period of integration.

Usually the capacitor is then discharged and a new period of integration is started.
T, the time for one period of integration. It is presumed that \( S \) is normally closed and is opened at the beginning of each period of integration, and left open for the integrating period. The unit is usually recycled automatically by having \( S \) close momentarily at some preset value of output voltage so that the unit returns to zero and continues to integrate.

\( t \), the time from the beginning of the cycle.

\( i \), the input current from the source. It is presumed that the dc amplifier uses no input current.

The voltage on the capacitor is then

\[
e_c = \frac{1}{C} \int i \, dt = e_i + e_0 = e_0(1 + \frac{1}{A}),
\]

The input current is given by

\[
i = \frac{e_s - e_i + \epsilon}{R} = \frac{e_s - \frac{e_0}{A} + \epsilon}{R},
\]

so that

\[
e_0(1 + \frac{1}{A}) = \frac{1}{RC} \int (e_s - \frac{e_0}{A} + \epsilon) \, dt;
\]

expanding this, we obtain

\[
e_0(1 + \frac{1}{A}) = \frac{1}{RC} \int e_s \, dt - \frac{1}{AR} \int e_0 \, dt + \frac{1}{RC} \int \epsilon \, dt
\]

at the end of the period of integration. Then

\[
E_0RC \left(1 + \frac{1}{A}\right) = \int_0^T e_s \, dt - \frac{1}{A} \int_0^T e_0 \, dt + \int_0^T \epsilon \, dt.
\]

Presuming that \( e \) increases fairly uniformly with time—that is, \( e = \frac{E_o}{T} \) -- and presuming that \( \epsilon \) does not drift during the cycle, we have

\[
\int_0^T e_s \, dt = E_0RC + \frac{E_oRC}{A} + \frac{E_oT}{2A} - \epsilon T;
\]

since we wish to have \( E_0RC = \int_0^T e_s \, dt \), then the last three terms of the above equation are errors and should be much less than \( E_0RC \).

Therefore, for satisfactory operation we must fulfill the following three requirements:
1. \( E_o RC \gg \frac{E_R C}{A} \),

2. \( E_o RC \gg \frac{E T}{2A} \),

3. \( E_o RC \gg \epsilon T \).

Reducing these, we have

1. \( A \gg 1 \),

2. \( ARC \gg T \); since \( E_o = \frac{E_{s T}}{RC} \), then \( T = \frac{E_o}{E_s} RC \); therefore we must have \( A \gg \frac{E_o}{E_s} \).

3. \( \frac{E_o}{\epsilon RC} \gg T \).

These are the necessary conditions for operation, and the errors are summarized as follows:

1. Per unit error due to insufficient gain = \( \frac{1}{A} \).

2. Per unit error due to low input voltage or impedance

\[
\frac{E_o}{2AE_s} = \frac{T}{2ARC}.
\]

3. Error due to inaccuracy and drift in the zero set = \( \frac{\epsilon}{E_o} \frac{T}{RC} \).

Since \( R \) is essentially infinite when a current source is used, the last two errors are zero for ion chambers or equivalent sources.

Conclusions

For satisfactory operation of a dc feedback amplifier of this type as an integrator from a voltage source, the following conditions are necessary:
1. The gain must be as high as possible and at least equal to the inverse of the expected error.

2. The average applied voltage times the amplifier gain must be much greater than the ultimate output voltage of the unit. This is because the input to the amplifier rises and cancels out part of the input voltage as the integration proceeds. In some cases when pulses are integrated the pulses may be well above the required voltage, but owing to the low duty cycle the average voltage may be much too low. The result is that a large error is produced by leakage back through the source. If a short is placed across the input the applied voltage is zero and the feedback is nullified entirely, so that the unit seeks the operating point that it would have without feedback.

3. The voltage due to the error in zero setting tends to charge the capacitor indefinitely when a return path to ground is provided by a grounded source. If the source impedance is high enough so that the total charge collected during the integration period is negligible then it can be neglected. If, however, a low impedance is placed across the input the output rises to the point at which the errors in Items 2 and 3 are equal and opposite. That is the point at which the output is equal to \( A \) times the error in zeroing.

* * * * * * *

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Fig. 1. Diagram of 100% inverse feedback electrometer for voltage integration.
\[ e_i - e = e_s \]

\[ -e_0 = -Ae_i \]