VOLTAGE AND CURRENT TRANSDUCERS

FOR ACCURATE HIGH VOLTAGE MEASUREMENTS

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1. GENERAL

The term "transducer" is defined here as a device which converts a high-voltage, or a high-current, into a low-voltage replica signal, possessing an accurately known and stable ratio, a small or accurately known and stable phase angle, and a sufficiently wide bandwidth that will include the fundamental and all harmonics of interest. The output voltage of such a transducer would be in the 5 volt level, a magnitude that is equally acceptable to analog and digital measuring and computing circuitry.

The input to such transducers could be anywhere from a few hundred volts to a few hundred thousand volts for voltage, and anywhere from one to several thousand amperes for current.

One could, therefore, consider the voltage transducer as a simple ratio device having a ratio range of 100...100,000 to 1. The current transducer could be considered as a shunt ranging in value from 0.001 to 10 ohms, approximately.

2. VOLTAGE TRANSDUCERS

Several arrangements of voltage transducers can be considered. These are:

- voltage transformer,
- resistive divider,
- capacitive divider,
- amplifier aided divider.

2.1 Voltage Transformers

The voltage transformer is probably the most reliable device for this application. Its main advantages are an isolated, low impedance output. Because of non-linearities of the core material, however, the voltage transformer is accurate only over a limited voltage operating range. To provide the required 1000 to 1 range of ratio, one is forced to use multiple units if good accuracy is to be maintained. Because of multiple unit requirements, a further disadvantage of the voltage transformer is the necessity of switching the high-voltage lead. This affects safety and flexibility of operation and prohibits range changing under load. High accuracy voltage transformers would typically feature shielded windings which would result in a very high common mode rejection ratio. They would also be capable of supplying substantial power to the load without deterioration of accuracy.

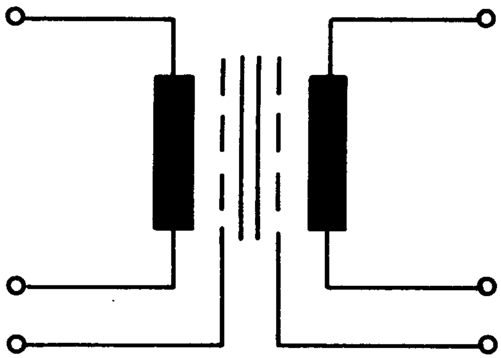


Figure 1. Double shielded potential transformer.

2.2 Resistive Dividers

Resistive dividers are very convenient and economical for the measurement of lower voltages. When tens or hundreds of kilovolts are to be measured, four problems are encountered. These are:

- power dissipation,
- shielding,
- phase shift,
- high output impedance.

These problems are inter-related, in that a low power design suffers adversely from a large phase shift, for example. Dividers that could operate at a known and reasonable phase shift at tens of kilovolts have to dissipate kilowatts in the divider. The high output impedance of such dividers is also limiting their application. In most instances the divider is used as an integral part of the equipment, thereby avoiding the loading problems.

For this and other reasons, the resistive dividers have been abandoned in favour of the capacitive dividers.

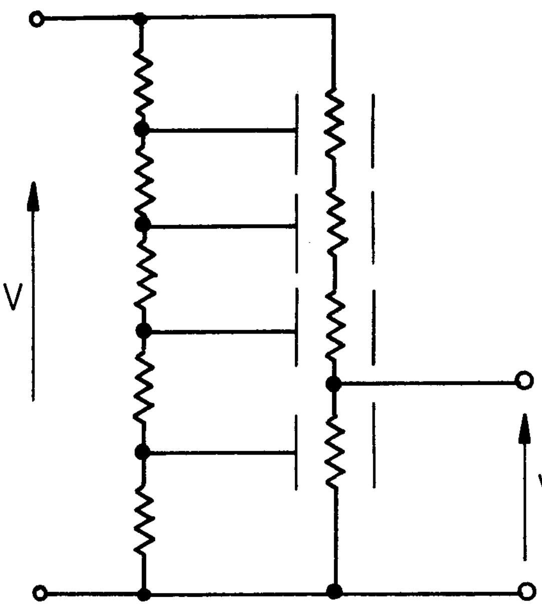


Figure 2. Shielded resistive voltage divider.

2.3 Capacitive Dividers

The popularity of capacitive dividers for accurate measurement of high voltages is due to several good reasons. The main reasons for this are:

- no power loss is associated with a capacitive divider.
- capacitors can be made inherently self-shielded.
- dielectrics that exhibit very little loss.
- capacitor designs that exhibit little, if any, voltage and temperature coefficient.

The above points refer to the high-voltage portion of the divider. The low-voltage portion of the divider, which typically would use a solid-dielectric capacitor, controls the performance of the divider. In spite of the above mentioned advantages of the high-voltage portion, the ordinary capacitive dividers are not capable of providing the performance required for accurate power measurement at low power factors. It is the availability of solid-state electronics, with high-performance operational amplifiers, that has made great improvements in accuracy possible. These are discussed next.

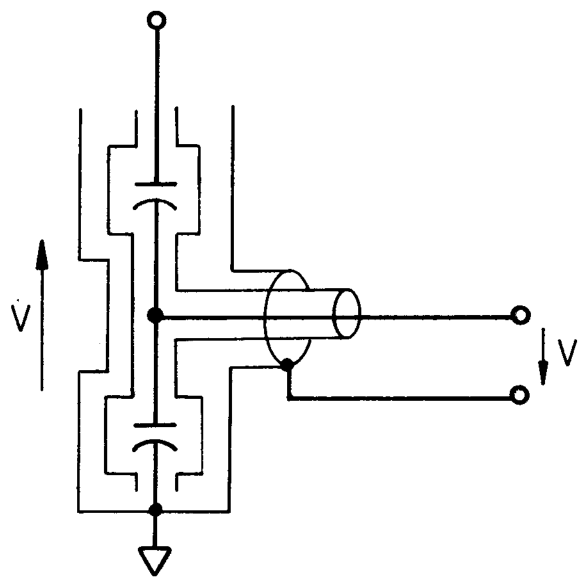


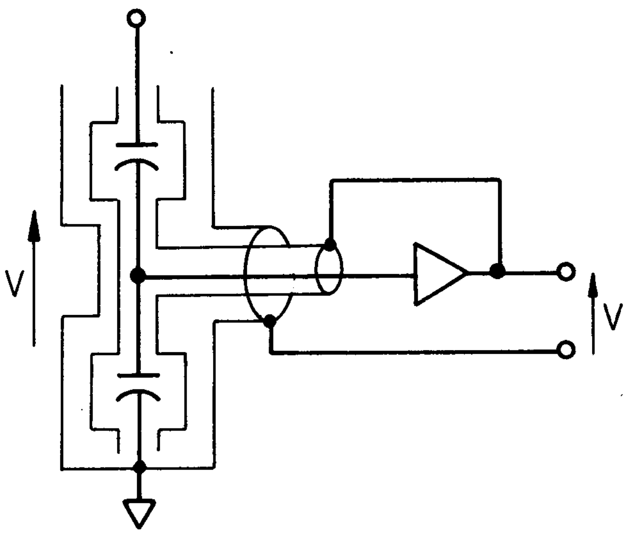
Figure 3. Shielded capacitive voltage divider.

2.4 Amplifier Aided Dividers

The problem of all passive dividers is that they provide a high impedance output. The addition of any load, including an additional length of cable affects the ratio, or phase of the divider. Amplifiers, when used with a divider, provide isolation and a low impedance output.

Two common configurations of amplifier aided dividers are possible, namely the inverting and the non-inverting types. The non-inverting divider is not inherently shielded. It requires the shield to be driven at the output voltage from a low impedance source. The inverting divider is more favoured because its shield operates at ground potential. This simplifies the circuitry and improves accuracy.

The wide acceptance of the inverting divider requires the use of a low-loss capacitor of high value. Since such capacitors are typically made of temperature stabilized plastic films, they exhibit a loss of about 200 micro-radians. This loss can be compensated, however, by the addition of a RC network.



igure 4. Amplifier-aided shielded voltage divider.

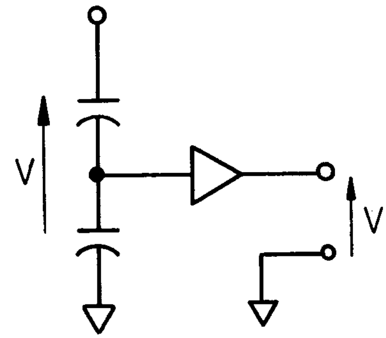


Figure 5. Amplifier-aided unshielded voltage divider.

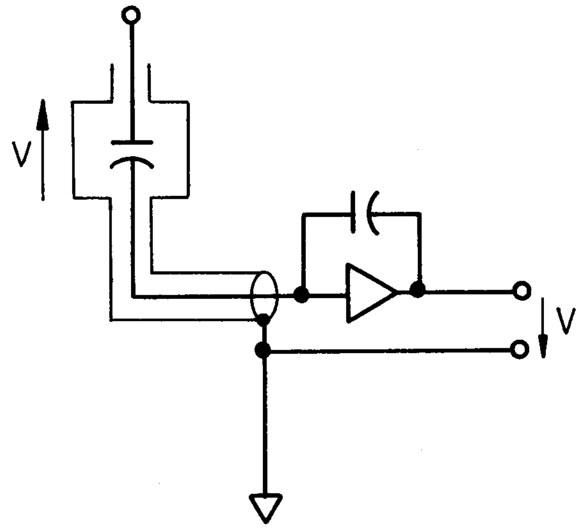


Figure 6. Amplifier-aided, inverting voltage divider.

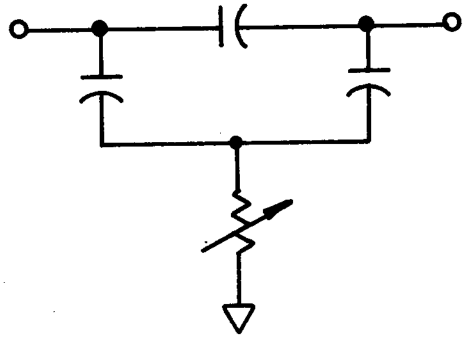


Figure 7. Compensated feedback capacitor.

Recent developments involving capacitors and current comparators have resulted in a potential divider that offers superior performance with respect to those discussed earlier. This divider uses two standard capacitors, thereby avoiding the losses and temperature instability of plastic components. By using a variable ratio current comparator, the instrument is capable of providing a wide range of accurate and stable voltage ratios.

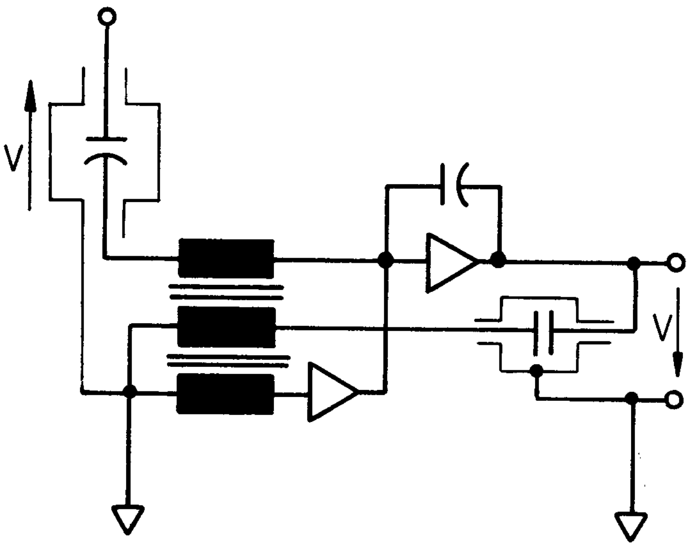


Figure 8. Current comparator based wide ratio range divider.

3. CURRENT TRANSDUCERS

Although several different principles for obtaining a signal proportional to current are available, there is only one principle, that of a current transformer, that is capable of delivering the accuracy and stability required. Some of the principles that have been studies and found to be inadequate include:

- mutual inductor-integrator,
- Faraday rotation,
- Hall effect,
- shunts.

For this reason, only the various configurations of current transformers shall be discussed here.

Perhaps a word should be said about the shunts. Although very high accuracy shunts are available, due to the requirement of galvanic isolation, they have to be used with some form of isolating medium employing analog modulation or digital coding. It is the poor performance of the isolating medium that makes shunts inadequate, for the application at hand.

3.1 Current Transformers

The accuracy of current transformers depends primarily on:

- ampere turns,
- permeability of core material,
- burden.

High accuracy CTs can be easily built by:

- using high permeability nickel-steel core,
- increasing the turns to increase the ampere turns on the core,
- choosing a low current on the secondary which reduces both the internal and external burden.

There is, however, a finite limit to the turns that can be used on a CT, and therefore the accuracy. The limit is the capacitive shunting current which increases as the number of turns are increased.

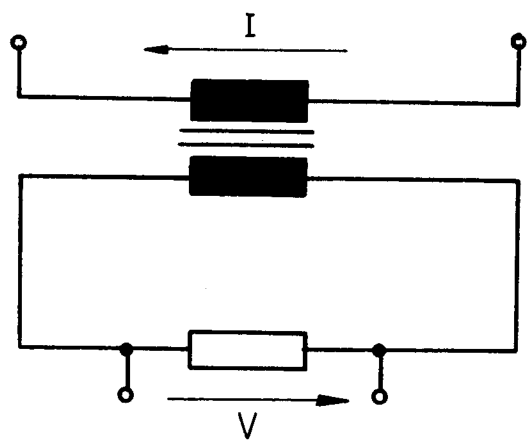


Figure 9. Current transformer with resistive burden as a current transducer.

To provide the wide range of current ratio required, one could use a CT with a tapped primary winding. This solution of providing range changing is undesirable, however, because it requires a high-voltage, high-current switch, or a manual connection for the required ratio.

Since precision current transformers may be large due to the size of the core and the larger number of turns, engineers and scientists have been coming up with configurations and circuits that offer high accuracy without the use of large cores or large numbers of turns. Some of these configurations include the two-stage current transformer, and a host of other compensating circuits employing active or passive components. These shall be discussed in turn.

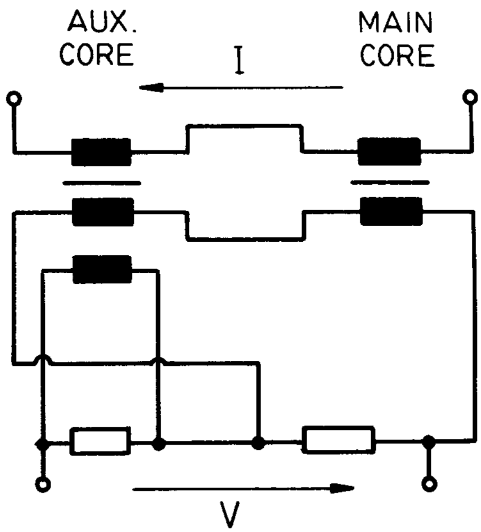


Figure 10. Current transducer based on the two-stage CT principle.

3.2 The Two-Stage Current Transformer

Almost seventy years ago, Brooks and Holtz published information on a two core, three winding CT configuration that is capable of reducing the CT errors by several orders of magnitude. The method employed here was that of reducing the burden and therefore the flux in one of the cores. By reducing the total burden by two orders of magnitude, the errors of the configuration would be reduced by two orders of magnitude. This configuration provided two currents that required addition. This severely limited the application of the invention and it was therefore not generally accepted by the industry. When used as a current transducer, however, the output of the two stage current transformer can be easily added to provide a transducer that is accurate and stable to parts per million. The addition of the required signals can be done passively, or actively by using a high performance operational amplifier.

When used for a transducer, the two-stage CT configuration can be easily cascaded to provide a large range of precise ratios.

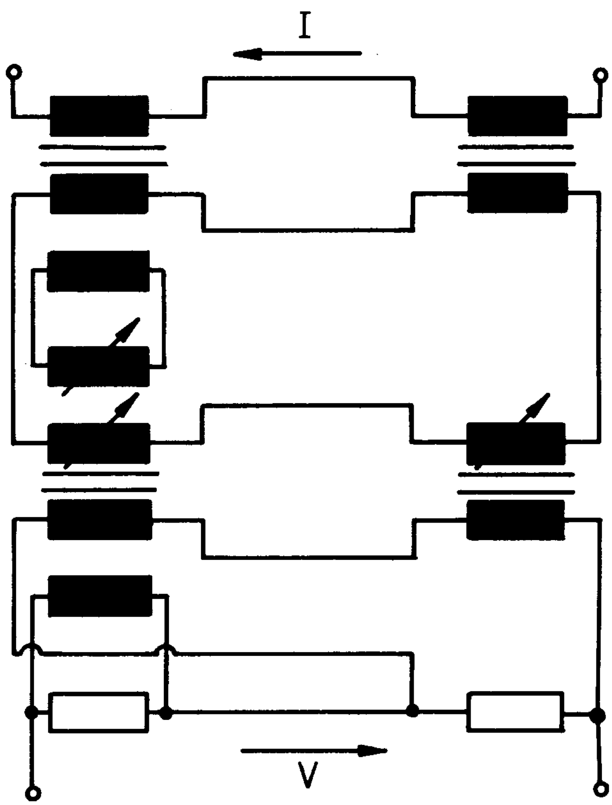


Figure 11. Wide-range current transducer using two, two-stage CTs.

3.3 The Zero Flux Current Transformer

Some twenty years later a CT configuration known as the zero-flux CT was patented by Hobson. This invention, similarly to the two-stage CT, also used two cores and three windings. Its chief advantage was one output. Its main disadvantage was the need for a compensating burden which would be linear and equal to the connected burden. The accuracy of this configuration is very good provided that the cores are equal and the internal and external burdens of the secondary and compensating circuits track. Under such conditions, the flux in the compensating core is doubled, while the flux in the main core is reduced to a very low density. This provides the required high accuracy.

It should be pointed out that the name "Zero flux CT" is misleading. The flux in the core is not inherently driven to zero, but is done so by the adjustment of a compensating burden. The errors, in fact, can be easily overcompensated by the manufacturer or operator. The only way of monitoring the errors would be to monitor the core flux by means of a separate search coil.

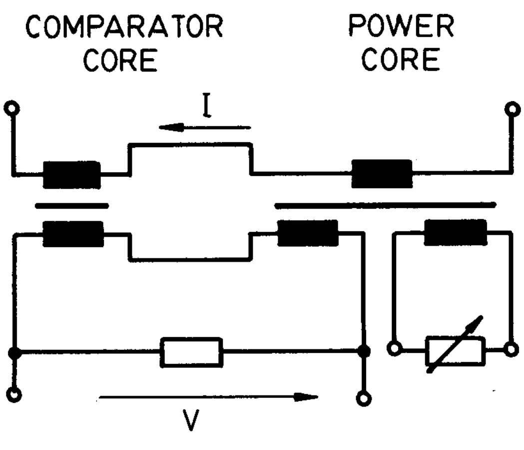


Figure 12. Current transducer based on the "Zero Flux CT".

3.4 Electronically Aided Current Transformers

There have been a variety of circuits published which use active electronics to reduce the errors of CTs by reducing the flux density in the CT core. Some of these use a single core, while other use two cores.

In all of these circuits, the active electronic circuitry is required to do one of the following:

- supply the core losses,
- supply all of the power required by the secondary circuit,
- supply a portion of the power required by the secondary circuit.

A handful of these circuits are discussed below.

3.4.1 Single-Core Configurations

The single core configuration of an amplifier aided CT has, in addition to the primary and secondary, an additional winding which senses the core flux. The signal from the sense winding is amplified and helps to drive the secondary current through the burden. The improvement in performance depends on the gain of the circuit. Circuits exhibiting large gain are difficult to stabilize, and therefore large improvements in accuracy are not possible.

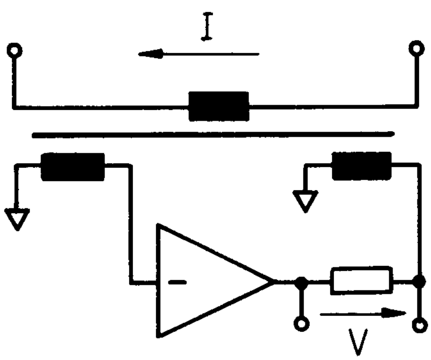


Figure 13. Single-core, amplifier aided, current transformer.

For circuits where the secondary is required to be totally isolated from the amplifier, an isolating transformer can be used. This circuit is even less stable than the original, all due to the addition of an extra pole in the feedback loop. The amplifier is required to supply most, if not all, of the power loss in the secondary circuit.

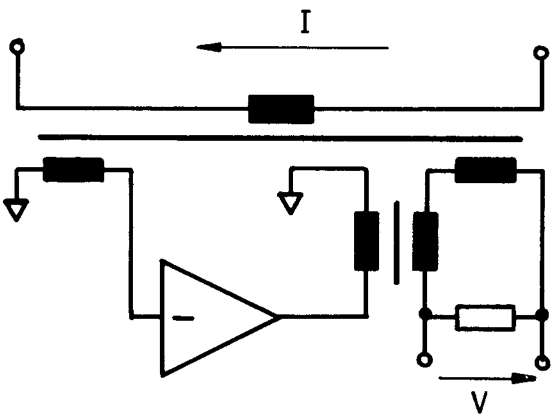


Figure 14. Single-core, amplifier aided, current transducer with isolated output.

3.4.2 Two-Core Configurations

The main advantage of the two-core configuration is that the amplifier requires to supply only a very small portion of the power required by the secondary circuit. Some of the configurations are based on the two-stage CT, while others are based on the zero flux CT designs.

One of the earlier circuits is that developed by A. Hobson which is based on his zero flux CT. Instead of using a compensating burden to reduce the flux in one of the cores, an amplifier is driven from a sense winding and its output is applied to the second core. Similarly to the single core configurations, the amplifier gain must be maintained high enough to reduce errors, yet low enough to avoid oscillation of the circuit.

The circuits to be discussed next, are those of the amplifier aided two-stage CT. The use of electronics has made it possible to add the two currents obtained from a two-stage CT. Maljanic has cleverly accomplished this by elevating the potential of the compensating winding to the voltage across the load, and having the amplifier force the compensating current through the load. A gain of only one is needed on the amplifier, thereby making the circuit very stable under all operating conditions. The accuracy obtainable is that of a two-stage CT, but the output is one current, rather than two.

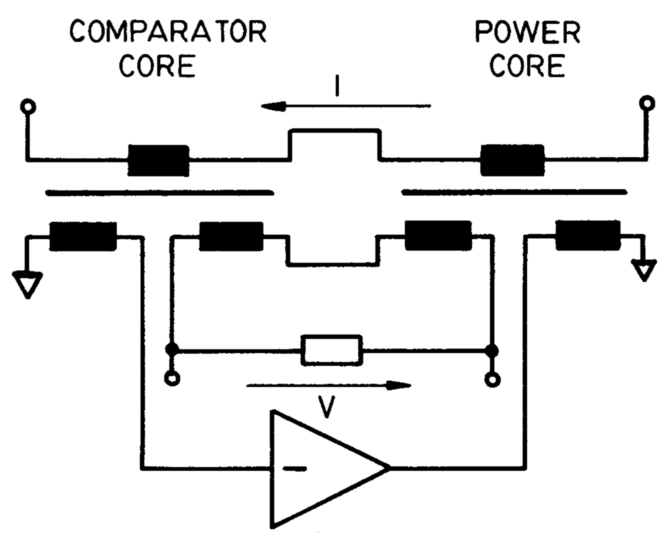


Figure 15. Two-core amplifier aided CT according to Hobson.

Another circuit, developed by Miljanic and Moore is also based on the two-stage design. In this circuit the compensating winding supplies a signal that is equal to the magnetizing current. With the aid of the amplifier, it is fed back to the CT to cancel the errors due to magnetizing losses. Unlike nulling circuits, the cancellation circuit is very stable under all conditions. Another advantage of this configuration is that the compensation circuit is isolated from the secondary.

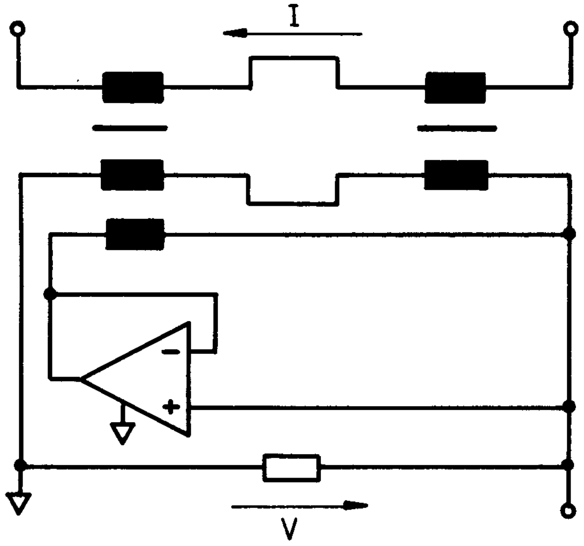


Figure 16. Amplifier aided two-stage CT according to Miljanic.

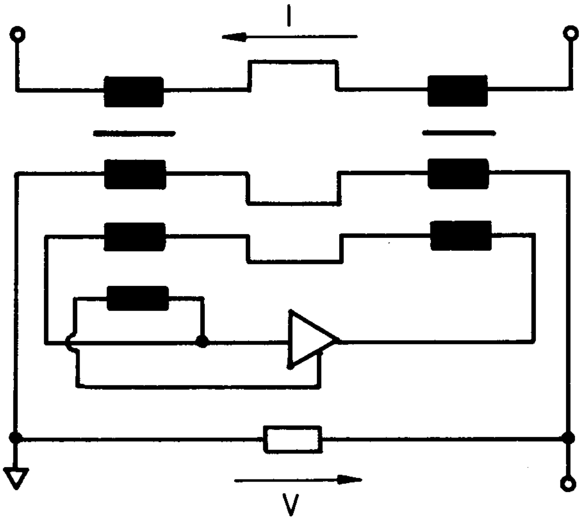


Figure 17. Amplifier aided two-stage CT according to Miljanic and Moore.

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