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PRINCIPLES OF A-C INSTRUMENTS [1]

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A-C Instruments

A Principles of Operation

1. A-C Ammeters and Voltmeters

a. A-C Instruments with D-C End Devices

(1) Thermocouple Type

A thermocouple instrument consists of a heating element, a thermocouple, and a permanent magnet moving-coil indicating mechanism. It may be used for the measurement of current (milliamperes or amperes) and also the measurement of voltage at high frequencies. It is relatively independent of frequency variations up through the Kilohertz range and milliammeters may be used up into the megahertz (million cycle/see) range. With suitable correction factors higher rated ammeters may be used in this range also. They are used primary for high frequency electric heating circuits and radio transmission and thus are often called R-F (radio frequency) instruments.

They depend for their operation on heating the junction of two dissimilar metals, particularly those widely separated (positive and negative) in the thermo-electric series.

This welded junction of the dissimilar metals is a "thermocouple". Heating is provided by a resistance wire to which the thermojunction is thermally joined, usually by welding. In some types, however, the thermojunction is insulated from the heater wire. The thermal emf at the ends of the thermocouple wires is a function of the current flowing through the heater wire and the d-c instrument is calibrated accordingly. The current thru the heater may be either d-c or a-c - the heat produced is the same. For voltage measurement, a suitable resistor is connected in series.

Some thermocouple combinations and their thermal emf for a 100° c difference are:-

Chromel (+ 2.80) - Copel (-4.50)
Chromel (+ 2.80) - Copnic (-3.51)
Platinum Iridium (+1.40) -
Gold Palladium (-3.80)

For accurate measurement it is necessary that the cold ends of the thermocouple be mounted in close thermal contact (but electrically insulated from) large flat terminal blocks. By so doing the heating in the heater wire, usually of platinum iridium, is added to the temperature of the terminals, thus eliminating the effects of self heating and ambient temperatures. Fig.1a

Since the heating of the thermocouple varies as the square of the current (I^2R) the output will produce a square-law scale on the d-c indicating instrument. This means that readings normally cannot be made below 20% scale. To overcome this difficulty, therefore, instrument pole faces may be shaped to give a narrow gap at the low end of the scale and a wide gap at the high end. This improves the scale uniformity at some sacrifice in overall instrument sensitivity.

Because of the low voltage output of a standard thermal junction a bridge arrangement is possible in which an even number of thermocouples are connected with the same number of couples in each bridge arm and the d-c output taken off at the center points.

A much less complicated circuit and yet one with output greater than that of a single thermocouple is the modified bridge arrangement shown in Fig. 1(b). Two heater wires of different materials (one positive and one negative in the thermal series) are connected in parallel to the two terminals. A wire of the opposite polarity is then added to the center of each heater, resulting in two couples in series.

To decrease heat loss and increase output, particularly on milliampere ratings, vacuum thermocouples are used. Thermocouple overload is limited to 1.5 or 2 times rated value.

(2) Rectifier Types

For voltage or low-current measurements where low power consumption is required, rectifiers are used in conjunction with a D-C instrument. The rectifiers are semi-conductors, originally of the copper-copperoxide type, later using germanium and more recently silicon diodes.

Simple half-wave rectifiers have been used but are inefficient and on the negative half cycle are subjected to full line voltage and possible breakdown.

The most common arrangement is the bridge circuit shwon in Fig.2. Here four rectifiers are used with the voltage applied across two junctions and the D-C instrument across the two others. This is a "full-wave" rectifier, using the entire A-C wave and thus is always conducting. Here we are concerned only with the forward resistance of the rectifier and there is usually no breakdown problem.

Rectifiers are fairly insensitive to frequency up to about the 3 Kilohertz range. Somewhat higher ranges are possible with silicon rectifiers.

Since the d-c output of the rectifier is the average of the A-C wave a rectifier instrument is actually measuring average rather than R.M.S. values of the a-c- voltage or current applied. However, they are normally calibrated in terms of R.M.S. current or voltage on a sine-wave circuit. If there is a variation in wave shape and the Form Factor of the A-C wave is not 1.11 then some error will exist in the reading. However, since most modern A-C generators have excellent sine-wave outputs, wave form error is not usually a serious problem.

The scales of low rated A-C rectifier voltmeters (i.e. below 5 volts) are usually somewhat constricted at the low end, since the rectifier forward resistance values are always much greater when a low voltage is applied.

The original copper-oxide rectifiers had a noticeable drift characteristic with time and thus rectifier instruments were usually given accuracy ratings of 3 to 5%. Modern silicon rectifiers are very stable and normal calibration accuracies will apply.

b. Iron-Vane Types

(1) Repulsion Types

These types depend for their operation on the repulsion effect of a pair of fixed and moving magnetic vanes of the same polarity. They are characterized by good torque-producing effectiveness (or low power losses for a given torque value) and fairly uniform scale distributions. The following are two common types.

(a) Wedge type (Fig.3)

Here a cylindrically formed wedge of magnetic material (usually a nickel iron alloy such as nicaloi or mumetal) is molded or cemented to the inside surface of a circular coil form. The latter is wound with a large number of turns of fine wire for voltage measurement and a relatively small number of turns of heavier wire for current measurement. Mounted on the instrument shaft is a vane of magnetic alloy polarized with the same instantaneous polarities as the fixed wedge by the current in the coil. Thus the moving vane is repelled by the fixed wedge until its torque balances that of the control spring. Scale distribution can be controlled to some degree by the shape of the fixed wedge inside the coil.

(b) "Book" or "Sector" Types of Repulsion Instruments

These instruments operate on the same principle, one name drived from the fact that the fixed and moving vanes open up like pages in a book and the second name pertaining to the most efficient coil shape which is in the form of a sector.

In these types (Fig.4) the moving vane of magnetic material is mounted radially to the instrument shaft. Close to this vane at the zero position is a fixed vane also radial to the instrument shaft. Located inside the coil form, both vanes will have the same polarity and the moving vane will be repelled in an up-scale direction. Scale distribution is inherently good in these types and can be varied only by changing the angle between fixed and moving vanes at the zero position.

The scale angle is limited to a theoretical maximum of 90°, but since at that point the repulsion torque is zero, it is preferable to use a considerably smaller angle (such as 70°) to achieve the greatest uniformity.

(2) Inclined-coil type

The Thomson inclined-coil instruments operate on the principle that a magnetic vane when free to move, will align itself in the direction of the field in which it is placed. If a pair of vanes is attached at a 45° angle to a shaft and the moving system placed inside a coil tilted 45° degrees to the shaft axis, a torque will be produced approaching the vane and field alignment position, until it is balanced by the torque of the control spring. Starting the zero point about 75 degrees ahead of the flux position (coil and vane in line-Fig.5) will tend to expand the lower portion of the scale and give a better degree of readability to the scale as a whole.

The construction is simple and open with very good clearances and ease of assembly. For acceptable scale distribution it is limited to a 100 degree scale.

(3) Long-Scale Attraction-Repulsion Types

Magnetic-wedge type repulsion instruments are limited to approximately a 180 degree scale span. Beyond this point the scale becomes very constricted.

Thus, to achieve a scale angle of 240° to 270° the addition of an attraction torque is necessary. In the 250 degree A-C Ammeters and Voltmeters an attraction vane is inserted in each end of the coil attached to magnetic end shields, rotatably adjustable (see Fig.6). The main repulsion wedge and the moving vane are polarized alike by induction from the field coil flux and exert a force of repulsion. However, the inner edges of the attraction vanes adjacent to the moving vane have polarities opposite to the latter and exert a force of attraction at the part of the scale where the repulsion torque is diminishing. For control of scale end distribution the shields and attraction vanes may be rotated slightly.

Since Voltmeters and Ammeters have different scale reading requirements, they use different repulsion vanes widening the voltmeter scale at the most-used portion, and expanding the low end of ammeter scales.

Such instruments provide a high operating torque and a maximum scale length per unit area of panel space.

However, the large amount of magnetic material used increases the variation due to frequency and thus their normal operating frequency range is restricted.

(4) 180 Degree Repulsion Types

For low-priced moderately long scale ammeters and voltmeters the 180 degree repulsion type is being used in large quantities. While most repulsion types will not provide a 180 degree scale of acceptable scale distribution, a modern design in which the coil proportions are changed, a new shape of moving vane used, and a wide spacing provided between ends of the repulsion vane, has achieved this (see Fig.7a). By increased magnetic gaps, the sensitivity to electromagnetic variations has been reduced and many switchboard instruments of the 1% class are furnished with pre-determined printed scales, unusual in iron-vane instruments. The compact assembly shown in Fig.7b has resulted in decreased size and weight as compared to the normal 250° long-scale instruments. Performance characteristics are nearly equivalent with limited frequency ranges for the best accuracy.

c. Electrodynamic Types

In the pure electrodynamometer system, no iron is used and operation is based on the action between the current in fixed and moving coils (Fig.8a). They have a flexibility for use in many types of a-c and d-c measurements.

Since the field flux is proportional to the current in the field windings and the moving coil or armature flux is proportional to the current in the moving coils (usually two per element) the resulting torque is determined by the product of the ampere turns in the field and moving coils.

In voltmeters, both field and moving coils are wound with many turns of fine wire and connected in series, with another series resistance to limit the current. (Fig.8b).

In milliammeters, the field and armature coils are connected directly in series but since higher values of current become a problem for lead-in spirals, a shunt carrying the major part of the current is connected across the armature circuit.

Although the torque is proportional to the square of the current at any scale point, the instrument does not have a "square law" scale since the angular relationship between the coils varies with scale position. The usual scale is constricted at the low end, widening in the center, and constricted again toward full scale where the angular relationship results in a torque decrease.

These instruments indicate true RMS values of current and voltage and are relatively insensitive to frequency variations. A common range of operation is 25 to 125 hertz. There is no hysteresis on d-c measurements.

d. Expanded-Scale Voltmeters

Many A-C Voltmeters usually operate over a very narrow range of voltage depending on the standard rating of the supply source. Here it is often desirable to expand the scale in the operating range (for example 90 to 130 volts). While instruments with suppressed zero scales have been used in the past, the problems of zero adjustment and other inaccuracies resulting from torque decreases, etc. had made these instruments of questionable value. Hence, the use of expanded scale instruments of normal torque values, with zero appearing on the scale.

(1) Saturated Reactor Type

In voltmeters of this type a series reactor provides sufficient impedance to limit the scale indication to a very small angle until the lowest <u>operating</u> voltage is applied. The reactor is designed so that the iron in the reactor will saturate at that point thus offering little impedance to the circuit. (See Figure 9). The normal series resistance will then permit a sufficient flow of current to give high torque and a good scale distribution over the limited operating range. Zero is at the usual scale position, but the lowest readable point in the operating range may be only about 10% of scale length above zero.

Because of the use of the reactor, frequency compensation is required and this is provided by a capacitor connected across a portion of the series resistor. Operating frequency ranges are limited on this instrument and calibration at the normal operating frequency is recommended.

Saturation of the reactor iron also results in some sensitivity to wave-form variations, but with wave shapes having less than 5% 3rd harmonic, operation is satisfactory.

An electrodynamic voltmmet mechanism is the best suited to this application.

(2) Diode Bridge Type

This expanded-scale voltmeter circuit provides the greatest flexibility of design, permits lower voltage ranges, is insensitive to frequency changes, and uses as the end device a conventional D-C indicator. It is adaptable to either A-C or D-C use, with a full-wave rectifier used in the A-C application.

Fig.10 shows the bridge arrangement, having three resistor arms and a Zener Diode for the fourth arm. The rectified voltage is applied across two points and the opposite two points are connected to a low-voltage D-C Voltmeter of any design, but preferably one of reasonably high ohm-per-volt sensitivity (1000 or 2000 ohms per volt).

The bridge is balanced to give a very slight deflection above zero (say 1.5 to 2 mm) with the lowest range voltage applied. (This would be 115 volts on a 115-125 volt scale). When voltages below this value are applied the instrument will read zero, or rest against the zero stop. On higher voltages, the voltage across the Zemer Diode will remain constant and that across the adjacent resistor arm will, therefore, increase, thus unbalancing the bridge. Current will then pass through the instrument coil and result in an upscale indication. Adjustable resistors are provided for the voltage span and for balancing at zero position.

2. Wattmeters and Varmeters

a. Electrodynamic Type

Physically the electrodynamic wattmeter is the same as the electrodynamic ammeter or voltmeter. However, in this case the field coil is wound with few turns of heavy wire and carries the circuit current. The moving coil contains many turns of fine wire and is connected across the line potential, in series with a suitable current-limiting resistor (Fig.11). Lead-in spirals conduct the potential-circuit current to the moving coil. Usually these are separate from the torque springs. Torque is proportional to the ampere turn product of the field and armature coils ($T = KN_aI_a \times N_fI_f$). Since instantaneous values of current and voltage may be displaced by a phase angle the indication will equal $E \times I \times \cos \theta$ or watts.

Two-element polyphase wattmeters are constructed with two sets of current (field) coils acting with two sets of moving coils mounted on a single shaft with four lead-in spirals and a separate torque spring, Fig.12. The readings of the two elements are additive and their total is a true measure of power on a 3 wire 3 phase circuit. Since 3-element indicating instruments are not feasible for mechanical reasons, a 4-wire-3 phase wattmeter is provided with an extra set of current terminals connected to one coil in each of the two elements (these coils are connected in series). It is sometimes called a "2½ Element wattmeter", but more approximately a "3-current coil, 2-Potential Wattmeter". For most applications it will measure 4-wire, 3-phase power accurately and is subject to error only when currents or voltages become severaly unbalanced.

These instruments are quite insensitive to frequency variations and are usually recommended for a frequency range of 25 to 125 hertz.

b. Iron-Cored Electrodynamic Type

This design provides two improvements over the conventional electrodynamic type without iron, namely, more uniform scale distribution and a higher torque per watt of power expenditure. The size of the mechanism can be reduced also. Construction is similar to that of a permanent-magnet moving-coil instrument, except that the permanent magnet is replaced by an electromagnet. The current coil is wound on an assembled stack of nickel-iron laminations having a circular air gap and a central core providing a uniform gap and uniform flux density. The moving coil is similar to that of the D-C moving coil instrument and serves as the potential coil in series with a high resistance (Fig.13).

As in the simple iron-less electrodynamic instrument the indication is proportional to the product of the amper-turns in the fixed and moving coils. Since the current and voltage may be displaced by a phase angle θ the instantaneous product will be E x I x cos θ, or a correct measure of watts. Since the iron in the magnetic circuit gives a slight phase displacement compensation is provided by a small capacitor shunting a portion of the series resistor.

Because of the uniform magnetic air gap the wattmeter scale is essentially linear.

C. 250° Scale Electrodynamic Type

This instrument represents a special class of iron-cored electrodynamic instruments having the magnetic field iron shaped to give a uniform air gap more than 250 degrees in length. The magnetic field material is in the form of nickel-iron punchings and these are inserted individually into the field coil form before being riveted and cemented together. An opening in the central core section is provided for the instrument shaft and mounted on one side of this shaft is the moving potential coil (Fig.14).

In principle it is identical to the 90-degree iron-cored type but the special moving coil and magnetic field circuit configurations are required to obtain the 250-degree full-scale deflection. Because of the amount of iron used phase-angle and frequency compensation are provided by means of a capacitor.

For polyphase measurements two field assemblies are mounted on a common base and the two armature (potential) coils are attached to a single long shaft.

d. Internal Transducer Types

Because of a growing tendency to use permanent-magnet moving-coil d-c indicating instruments as the end device for many measurements, wattmeters are now being built in this manner with internal power converters or transducers.

These are of two major types:-

(1) The Hall-Effect Transducer Type

When a rectangular wafer of a semi-conductor material, such as germanium or indium arsonide, is placed in an a-c electromagnetic field and excited by a small alternating current across the center of two opposite faces, there will be a d-c potential generated across the two remaining faces, proportional to the product of the a-c field strength and the alternating current applied. This is known as the "Hall effect" from its discoverer.

In the Hall-Effect power converter or "transducer" the current coil is wound on a magnetic core and produces an electromagnetic a-c field across the gap proportional to the current in the circuit (Fig.15). The semiconductor (usually indium arsenide in commercial types) is mounted in this gap and two opposite edges connected to the potential source, in series with a high resistance. Connections to the other two edges provide a d-c potential proportional to the product of the a-c potential and the current flux and thus gives a measure of a-c watts on a conventional d-c millivoltmeter.

The construction is simple and provides a good uniform scale. The output, however, is usually limited to about 1 milliampere at 50 millivolts and while suitable for some d-c taut-band instruments does not provide sufficient power for many other types.

2. Squaring-Resistor Transducer Type

The principle of these transducers is indicated in Fig.14. A center-tapped voltage transformer is connected to a resistor network with rectifier diodes in the outside legs. On the positive half of the wave current I_1 will flow, returning from right to left in the center leg of the circuit. On the negative wave I_2 will flow, but again will return from right to left in the center leg. Thus the center leg current due to potential excitation is always unidirectional.

However, the circuit current (through a step-down transformer) is applied across resistor R_C introducing a voltage drop which reverses every halfcycle. Thus the current through R_E is the sum of the current and potential circuit currents on one half cycle (e+i) and the difference on the reversed halfcycle (e-i). R_E is a squaring resistor which may be in the form of a non-linear semiconductor or a group of diodes which provide a voltage output proportional to the current flowing.

$$(e+i)^2 = e^2+2ei+i^2$$

$$(e-i)^2 = e^2-2ei+i^2$$

subtracting = 4 ei

Since the current and voltage are displaced by the phase angle of the circuit the output indicated on the d-c end device is proportional to ei cos θ, or a correct measure of circuit power.

This type is characterized by a relatively high d-c output (volts, rather than millivolts) and thus is more flexible in its application.

e. Varmeters (For Measuring Reactive Power)

The measurement of vars, which is the product of the voltage and the component of the current which lags 90-degrees behind the voltage; makes use of the conventional wattmeter mechanisms either of the electrodynamic type or of the transducer types. In any of these, however, the current in the potential coil must be lagged 90degrees behind the voltage.

1. In a single-phase varmeter an impedance network provides the 90 degree potential circuit current lagging, Fig.17. The impedances must be adjusted until the varmeter reads zero at unity power factor.

Since this network is frequency sensitive adjustments and calibration must be made at the frequency on which the instrument is to be used.

For a two-phase varmeter, current is taken from one phase and potential from the other phase. Otherwise standard wattmeter calibration will apply.

2. For measurement of vars on a 3 wire 3 phase circuit the most common method is the use of a double autotransformer, connections for which are shown in Fig.18. By the proper connection to a 3 phase voltage and the use of the correct transformer taps, voltages can be made available 90 degrees away from the line voltages E_{1-2} and E_{2-3} normally used

in 3 phase power measurement.

The calibration of the instrument is exactly the same as a 3 wire 3 phase wattmeter, except that the scale is marked in Vars, Kilovars, or Megavars. By appropriate switching the instrument also can be made to indicate either Watts or Vars.

3. Another method of obtaining the 90° phase shift, and that commonly employed in the measurement of 4 wire 3 phase vars, is the cross-phasing method shown in Fig.19. Where phase voltages e_{1-N} and e_{3-N} are normally used for power measurement, line voltages E_{3-2} and E_{2-1} are used, respectively for varmeters, each 90° behind the normal wattmeter voltages. Since these line-to-line voltages are 1.73 times the phase voltages, the instruments would be rated 208 volts instead of 120 volts and would have a special calibration constant.

3. Power-Factor and Phase-Angle Meters

These instruments may be exactly the same, with the exception that one is calibrated in Degrees Phase Angle and the other in Power Factor ($\frac{\text{watts}}{\text{volt-amperes}}$) or the Cosine of θ, the angle between voltage and current.

There are occasions, however, when a Phase Angle Meter measures the electrical angle between two voltage circuits.

a. Electrodynamic Single Phase Type

Earlier designs were built with conventional wattmeter current coils but with crossed potential (moving) coils displaced by 90 degrees.

One coil is connected to the potential circuit through a non-inductive resistor and the other in series with an inductive reactor, Fig.20.

When used on Unity power factor loads, the resistive coil will align itself with the current coils. As the power factor lags the torque on the inductive coil will increase and it will approach alignment with the current coils. This is a ratio instrument with no control springs, although light lead in spirals are used to conduct the current to the moving coil.

Because of the use of the inductive reactor, this type of instrument is frequency sensitive and should be calibrated at the specific frequency on which it will be used.

Some designs, instead of using a single element with a crossed coil armature will utilize a two-element electrodynamic instrument with the current coils connected in series and the two potential coils mounted at an angle of 90 degrees on the shaft. Otherwise the principle is the same (see Fig.21).

b. Electrodynamic Polyphase Type

The same construction shown in Fig.21 is used also for polyphase power-factor measurements. Here, of course, no reactors are used and the two potential circuits are connected to different phases with a series resistance in each circuit. For example, on a 3 wire 3 phase circuit, one potential coil would be connected to Potential E_{1-2} and the other to E_{3-2} with the current taken from line 2, the common potential connection point.

It is a ratio instrument with the lowest possible torque on the lead-in spirals. The two elements have opposing torques and the indicated reading occurs when these torques are in balance.

A standard scale is 0.5 (lag) -1.0 -0.5 (lead) but other ranges are possible and scales may be completely on the leading or the lagging side.

c. Polarized-Vane Type

These instruments are strictly phase-angle meters as the deflection angle equals the electrical angle. However, they are usually calibrated in Power Factor.

The potential circuit is in the form of a motor-type stator with distributed windings, connected to polyphase potentials. (When used on single-phase circuits, however, a phase-splitting network will provide the proper potential phase angle displacements to achive a rotating magnetic field). A moving-vane armature, consisting of a pair of vanes 180 degrees apart connected together magnetically by a sleeve of magnetic material. This is polarized by a circular current coil located inside the stator.

The magnetic field rotates at the rate of one revolution per cycle. The vane flux rises to a maximum, falls to zero, rises to maximum in the reversed direction and again falls to zero during each complete rotation of the magnetic field. The rotating field, of course, is reversed in polarity every half cycle. The coincidence of the maximum current flux values in the vanes with the instantaneous polarity of the revolving field gives a phase angle indication.

These instruments are normally calibrated for a 180-degree scale range of 0 (Lag) - 1.0 - 0(Lead),PF but where a reversal of current flow is possible, the scale can be marked over the full 360 degrees.

4. Frequency Meters

a. Resistance-Reactance Electrodynamic Type

Frequency meters of this type are physically similar in construction to the electrodynamic voltmeter, both sets of coils being wound for potential. However, instead of using a control spring, which would make the instrument sensitive to voltage magnitude, restoring torque is supplied by a magnetic vane in the center of the moving coil which tends to align itself with the field coil flux. (Fig.23).

Current passing through the moving coils splits between the two field coils, one in series with a resistance, and the other in series with a reactance. Circuit constants provide equal torques from the two field coils at the normal frequency and the instrument will indicate approximately center scale. Current in the resistive field coil circuit will not change with frequency but in the reactive circuit the current will decrease with an increase in frequency. Thus the instrument will deflect in an up-scale direction and is calibrated in hertz (or cycles per second).

This circuit is rather insensitive and require long scale ranges, such as 20 to 90 cycles.

b. Tuned Circuit Electrodynamic Types

To provide additional sensitivity and to shorten scale ranges, two tuned circuits replace the resistor and reactor of the previous type. One is tuned at a frequency below the range of the instrument and current, therefore is decreasing over the instrument scale. The other circuit is tuned above the instrument range and the current increases over the instrument range, Fig.24. The field coils are differentially connected and will respond to very small changes in frequency. Some common scales are

55 - 65 CPS 58 - 62 CPS	for 60 CPS operation
45 - 55 CPS 48 - 52 CPS	for 50 CPS operation

c. Mutual Inductance Type

In long-scale instruments where it is difficult to provide a restoring torque without adding a second element, mutual inductance instruments are used, in which the induced emf in the moving system coil resulting from the field coil flux is matched against the voltage across a tuned circuit. A reactor is connected between them for proper phase relations, (Fig.25).

When the two voltages are not matched a current will flow in the moving coil which will cause it to turn to a position where its induced voltage matches that across the tuned circuit. Then no current will flow, and a rest position is established. Adjustment is by means of the tuned circuit.

d. Tuned-Circuit Type with D-C End Device

This more recent design is in line with the trend to adapt all kinds of a-c measurements to a d-c indication. It has considerable flexibility in frequency values and scale sensitivities.

Input voltage is regulated by a group of zener diodes in series with a resistor. This constant voltage is fed into two net works, C_L and L_L being tuned below the desired instrument range, and C_H and L_H being tuned above the range. The current through these tuned branches is a-c but rectifier diodes give a direct-current flow through the instrument coils, differentially connected. Capacitors are connected across the instrument to reduce a-c ripple, Fig.26.

Differential ranges are provided by selecting the tuned circuit components.

e. Saturated Transformer Type

When a small transformer with a low cross section saturable leg is excited from an a-c source in series with a resistor, the voltage output under saturation can no longer be proportional to the primary voltage, but $E = 4 \pi f \phi m$, where f is the frequency, ϕ the transformer flux, and m the mutual inductance. With the flux and the mutual inductance held constant by saturation the output voltage is then directly proportional to frequency. This is rectified and applied to a d-c indicator, Fig.27.

Because of the direct relationship between frequency and voltage, it is not suitable for narrow frequency ranges but is useful for long ranges such as 500 to 1000 cycles.

5. Synchroscopes

a. Lamp Type

This early Weston type is described as a matter of interest, although it is no longer used.

The instrument is of the electrodynamic type with a pair of field coils connected through a series resistor to the incoming generator. The moving coil is connected through a capacitor to the running generator, or bus. When the two circuits are out of synchronism the phase relations are constantly changing and the moving coil will oscillate back and forth. However, the pointer is behind a translucent glass scale and illumination provided by a lamp behind the pointer. The lamp is excited from the secondary of a transformer with a double primary connected to each of the generators. Thus voltages are adding and subtracting causing the lamp to vary from full illumination to zero. Lamp fluctuations, together with the oscillating pointer give the illusion of a continuous pointer travel, to the left if the incoming generator is slow, and to the right if fast (see Fig.28).

b. Motor Type

Fig.29 shows a special bipolar motor used on synchroscopes for many years. The field windings are connected to the running generator or bus. The armature has two coils mounted at right angles. These are connected through slip rings to the incoming generator, one through a resistor and the other through a reactor, providing a rotating field. When the frequencies of the two generators differ the armature will rotate in a clockwise direction if "FAST", and in a counter clockwise direction if "SLOW". When in sychronism and in phase the pointer will be at rest in the 12 o'clock position.

This synchroscope uses a ball-bearing type of motor and power consumption is high (over 100 watts per circuit).

c. Differential Field Type

This is also known as the "Iron-Vane Type" since a group of magnetic vanes on a shaft are mounted inside a motor type stator with distributed windings. The two generators are connected to this stator through networks that produce equal fields rotating in opposite directions. The vanes align themselves with the field at the point where the two rotating vectors cross and the direction of motion indicates whether the incoming generator is fast or slow. Since no excitation is provided for the vanes they may assume two 180° positions at any point. Hence, a double ended pointer is used and synchronism is indicated when either end is in the center scale position. The pointer indicates 1/2 the phase angle separating the two machines. This instrument has low power consumption.

d. Polarized-Vane Type Synchroscopes

These are similar in construction to polarized-vane power-factor meters because they do actually measure the phase angle between two generators. Here, of course, both circuits are wound for potential.

A two-phase motor-type stator with distributed windings is connected to the incoming generator through a phase-splitting network to produce a rotating field. The vane is polarized by a potential field coil set inside the stator and connected to the running generator or bus, Fig.31. The polarized vane follows the rotating field of the stator at a speed equal to the difference of their frequencies or one revolution per cycle difference. At coincidence of frequency and phase angle the pointer will rest at the 12 o'clock position.

6. "Transducers" or Converters (Used with separate D-C Indicators)

There is a growing trend toward the standarization of D.C. permanent-magnet, moving-coil instruments as the end device for A-C measurements using what are popularly called "Transducers", but, more properly, Converters to change the AC measurement to a simple D-C signal.

They are used for measurements taken at a distance, or Telemetering, for a coordinated measurement system using standardized D-C indicators, for special types of measurements, and sometimes just to eliminate the special designs of instruments used for measurement of power, power factor, and frequency.

a. Current and Voltage Converters-Rectifier Type

These are the simplest types of Converters supplied and are basically only step down transformers with rectifiers to convert to D.C. However, several features are built into these to permit adjustments and greater flexibility of use; also to protect the Converter against abnormal circuit conditions.

A usual step-down ratio is from 5 to .010 Amperes, and from 120 to 10 Volts.

Full wave rectification is provided using silicon diodes for accuracy and permanency.

In the AC to DC Current Converters breakdown diodes are sometimes added to safeguard against an open circuited transformer secondary. Other refinements are the use of ballast resistors to give greater stability and to provide the proper voltage drop and a span adjustment to make allowance for variations in load and instrument circuit resistance. They normally provide for an output of .010 Amperes into a 1000-ohm load, Fig.32.

In A-C/D-C Voltage Converters a series resistor is inserted in series with the transformer primary to prevent any damage due to a short circuit. Ballast resistance is used also and a diode to compensate for non-linearity resulting from the rectifier. A span adjustment is provided also for final adjustment, and to allow for differences in lead and circuit resistance.

Both use capacitors to smooth out the A-C ripple.

b. Power (watt) Converters

(1) Heater and Thermocouple Type

In these so-called "Thermal Converters" internal step-down current and potential transformers are interconnected in such a way that the current is aiding the potential in one circuit (e+i) and opposing it in the next (e-i). In each circuit is a thermocouple with the D-C couple wires connected in series (Fig.33). Since the heating of the thermocouple heater wires is proportional to the square of the current flowing in each circuit, then

$$(e+i)^2 = e^2 + 2ei + i^2$$

$$\underline{(e-i)^2 = e^2 - 2ei + i^2}$$

Subtracting = $4ei$, or the product of

voltage and current. However, since these are displaced by a phase angle θ, then the output is proportional to ei cos θ, or a true measure of watts.

These are reliable devices, but are comparatively expensive and the millivolt output is low.

(2) Hall-Effect Type

Separate converters using this principle are available for general use. In principle, they are identical with the interally mounted "transducers" described in Section 2-(d)-(1). They are packaged separately, however, and are adjusted for a fixed millivolt output (usually about 50 MV). Filtering for a-c ripple is generally included and compensation for ambient temperature errors, Fig.34.

(3) Squaring Resistor Type

The separate watt converter for general use is a modification of the type shown in Fig.16 and described in section 2-(d)-(2). The principle of the sum and difference of current and potential is used, and squaring is provided by a group of diodes and resistors as shown in Fig.35. Span adjustment is provided to give an output of 1 milliampere through a maximum load of 2200 ohms.

c. Power-Factor or Phase-Angle Converters

One form of phase angle converter is shown in Fig.36(a). A potential transformer with a center tap is connected through rectifiers and zener diodes (ZD) to give a chopped wave output as shown in Fig.36(b)-A. However, connected to the center of the transformer secondary and the center of the resistors R_3 and R_4 is a transistor T which switches the circuit on or off when actuated by the circuit current. The figure shows a composite of the single phase and polyphase combinations though only one of these is used in a given converter. Since an initial phase angle of 90 degrees is required, the polyphase current source is connected through a resistor and stabistor diodes (to regulate the magnitude of the current wave) directly to the transistor. The switching operation is shown in Fig.36(b) B-C and D. At unity power factor (B), the current, which by the polyphase connection is lagged 90°, switches on the chopped potential wave and keeps it on for 180 degrees, or until the current reaches zero, when it is switched off. Thus, the plus and minus sections of the output wave are equal and cancel out, giving no deflection to a zero-center-scale d-c millivoltmeter, whose scale is marked 1.0 (unity P.F.) at zero center.

With the current leading, the transistor will switch on earlier and the positive half of the output wave will predominate ("C" shows condition at 0 P.F. leading) and the instrument will read up scale. With lagging current, however, the transistor will switch on later and the negative wave will predominate, until it is entirely negative at 0 P.F. lagging (D). The instrument will then read down scale and is calibrated in either Power Factor or Phase Angle.

The single-phase arrangement is the same except a network is provided to lag the current 90 degrees.

d. Frequency Transducers - Tuned Circuit Diode Type

This type is described because of its simplicity, its flexibility for different ranges, and its capability of short, high sensitive frequency ranges.

In principle, it is identical to that supplied in some frequency meters (Fig.26), described in 4(d). Zener Diodes z and a series resistor R_1 (Fig.37) regulate the voltage which is impressed on two resonant circuits one tuned above, and the other below the frequency range of the instrument. The current in the L side (low tuning) is decreasing, while that in the H circuit (High tuning) is increasing. The current in these two branches is alternating, but a rectified d-c component from both circuits is subtracted through resistor R_2 and the differential d-c millivolts appearing across the d-c output terminals is a measure of frequency, when applied to a center scale d-c millivoltmeter.

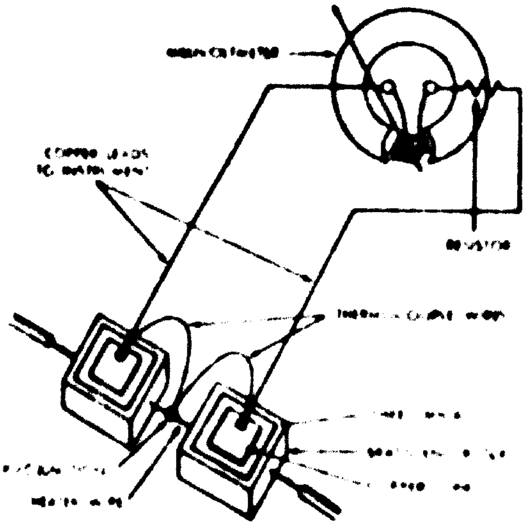


FIG. 1(a)

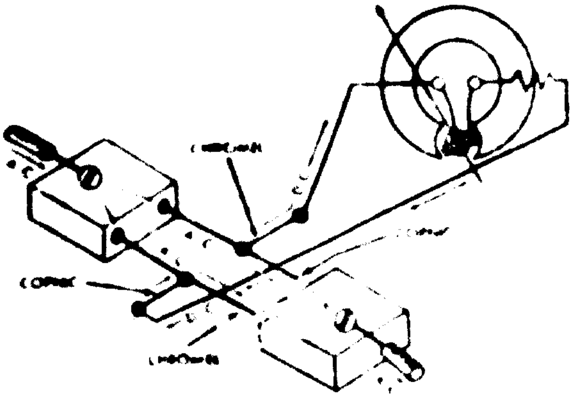


FIG. 1(b)

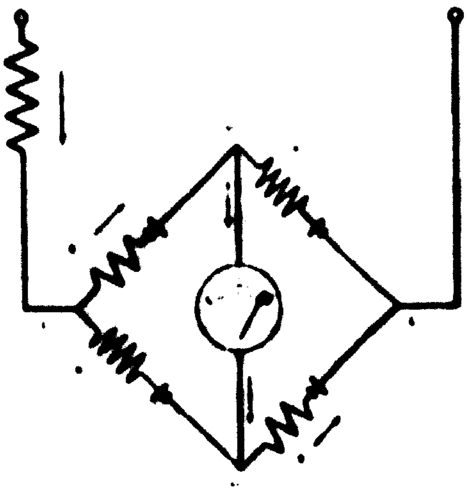


FIG. 2

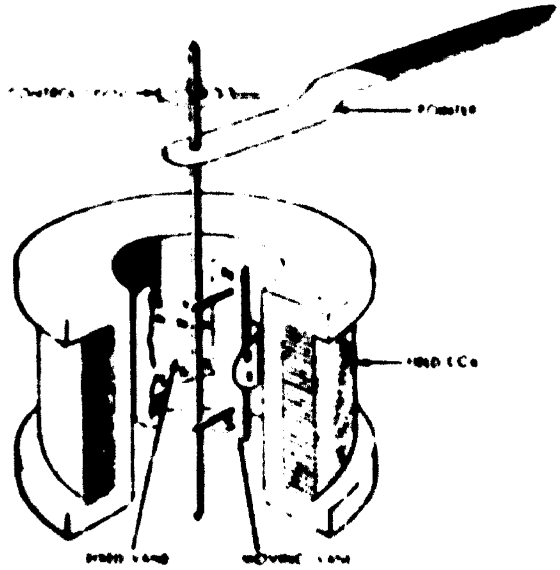


FIG. 3

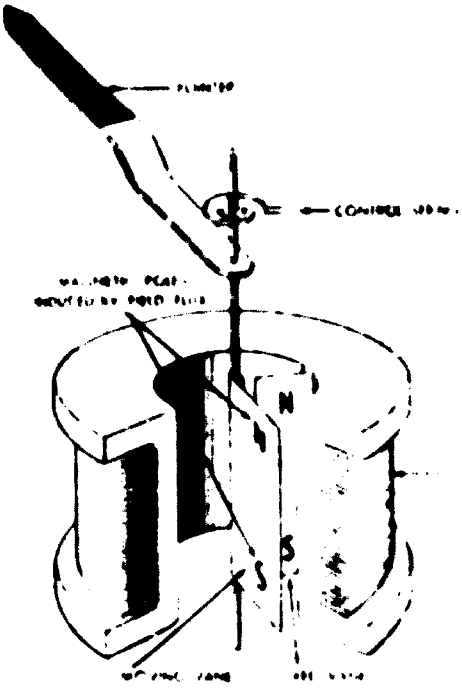
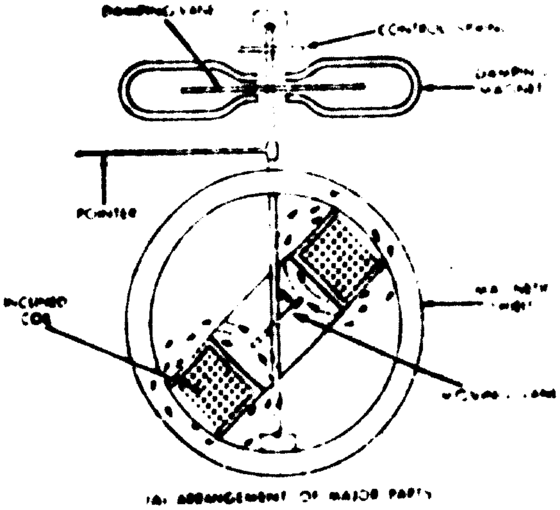


FIG. 4



(A) ARRANGEMENT OF MAJOR PARTS

FIG. 5

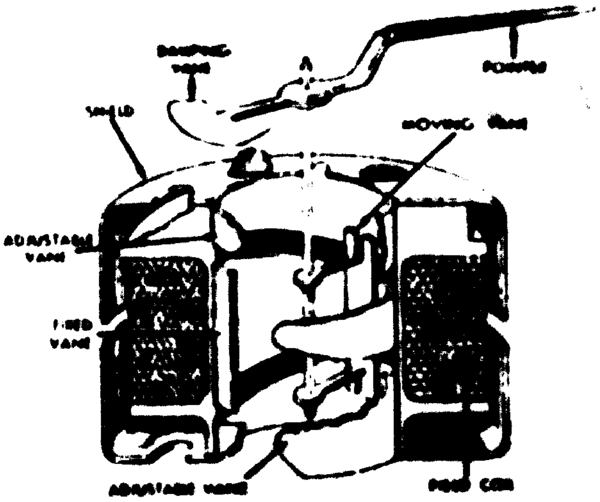
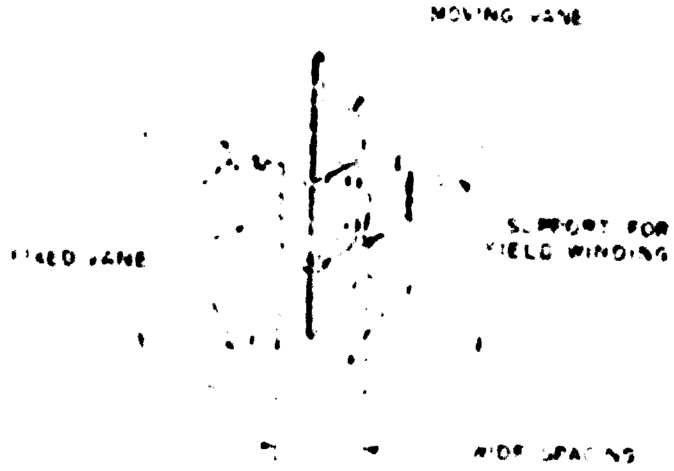
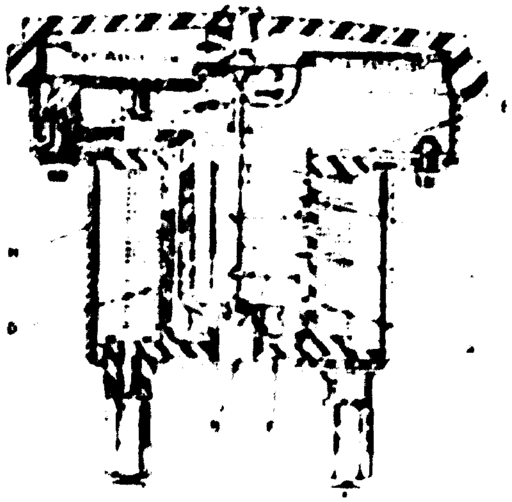


FIG. 6


MOVING VANE
FIXED VANE
SUPPORT FOR
FIELD WINDING
WIDE SPACING



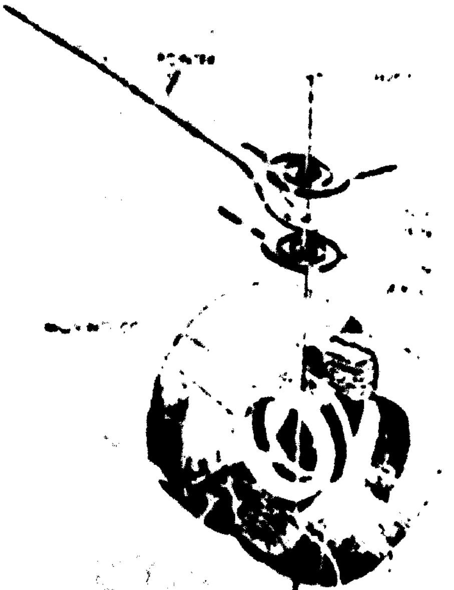

POINTER

FIG. 8(a)

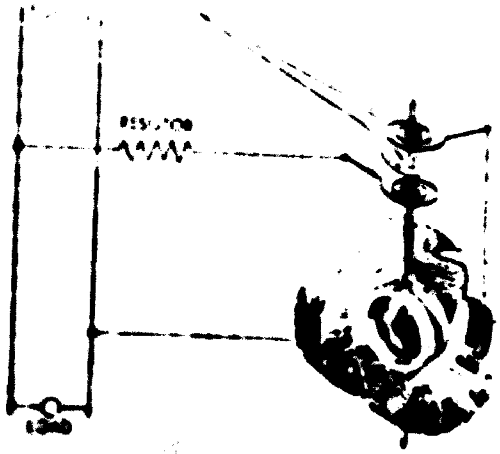

RESISTOR
LOAD

FIG. 8(b)

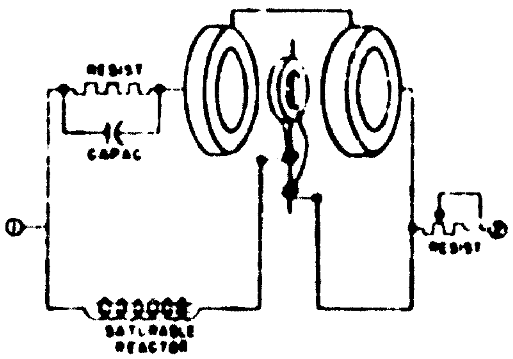


FIG. 9

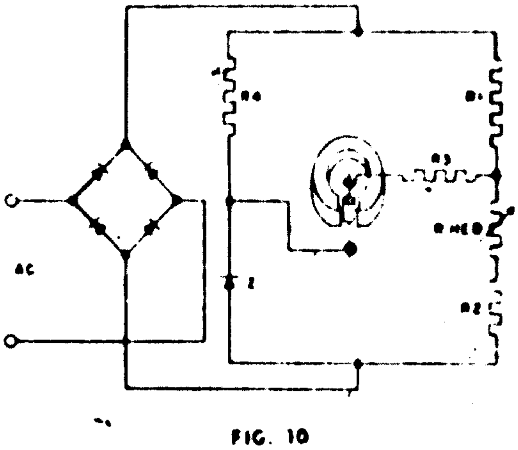


FIG. 10

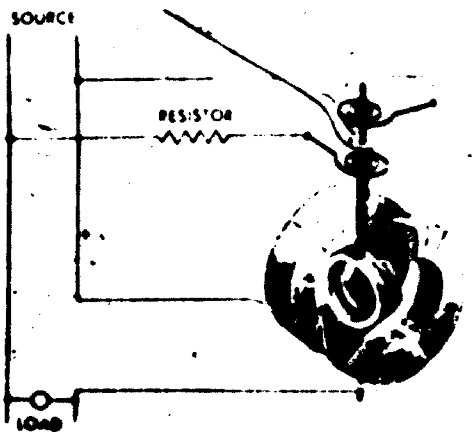


FIG. 11

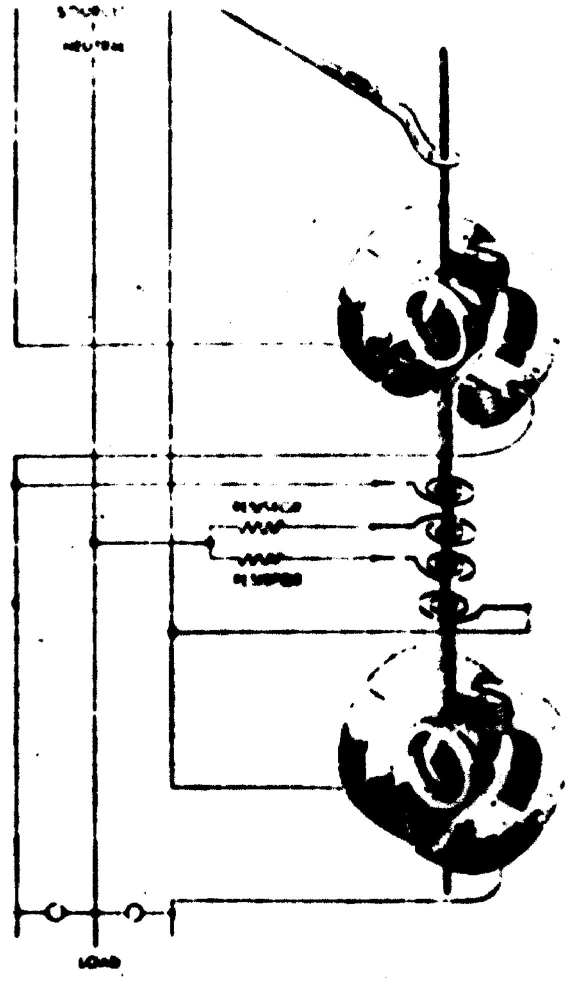


FIG. 12

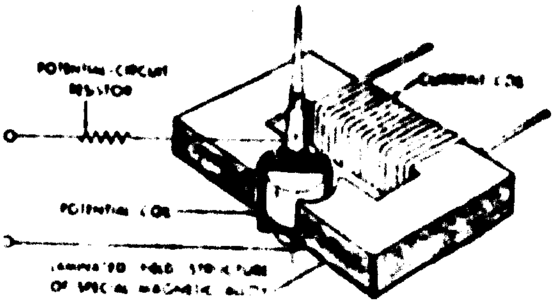


FIG. 13

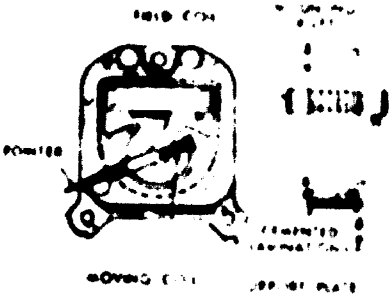


FIG. 14

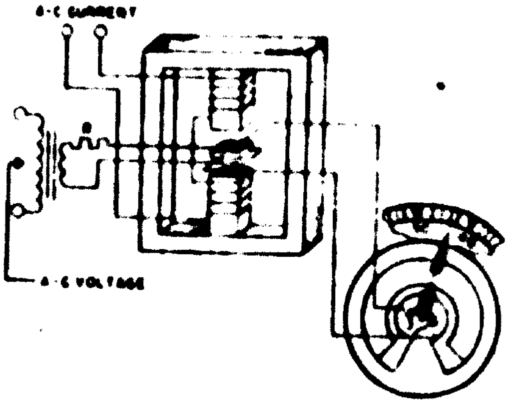


FIG. 15

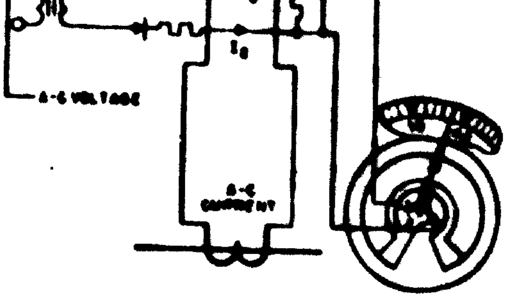


FIG. 16

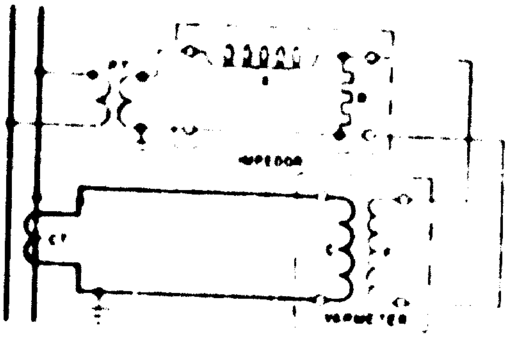


FIG. 17

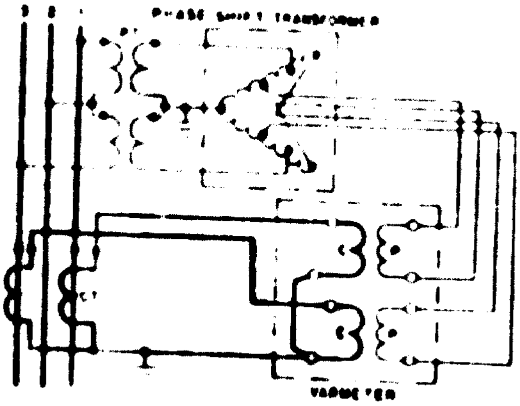


FIG. 18

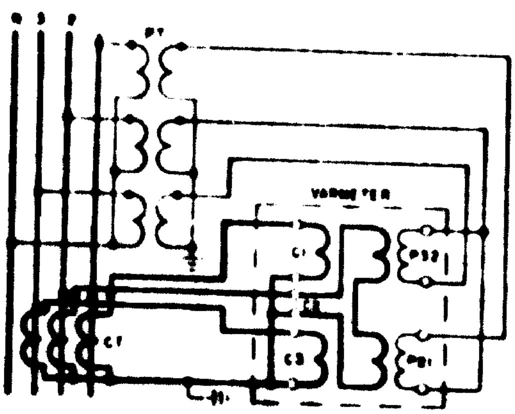


FIG. 19

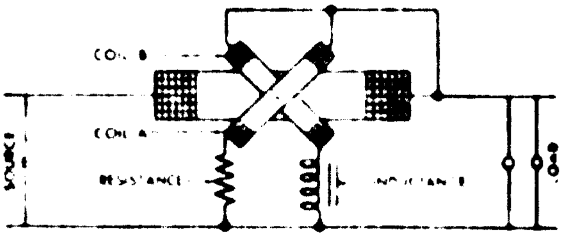


FIG 20

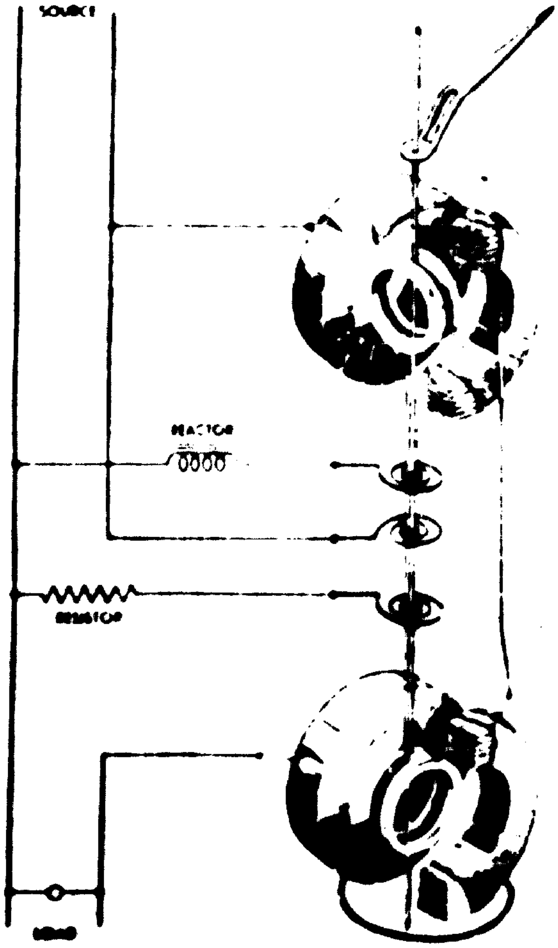


FIG. 21

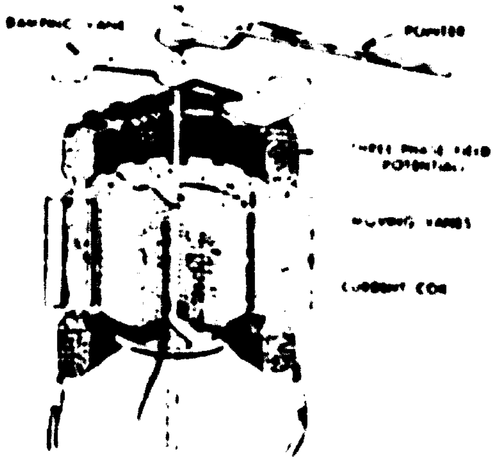


FIG 22

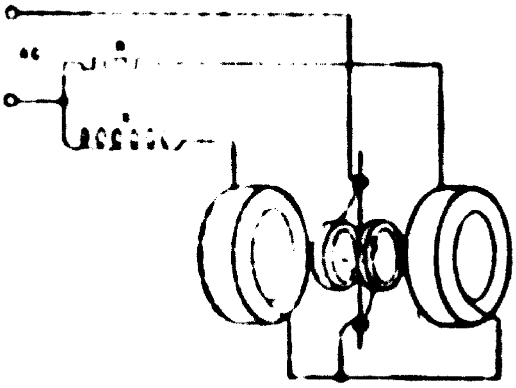


FIG 23

FIG. 24

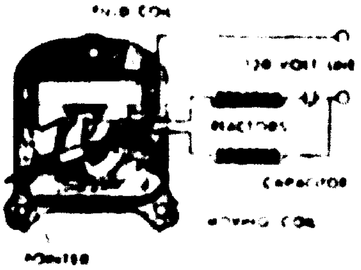


FIG. 25

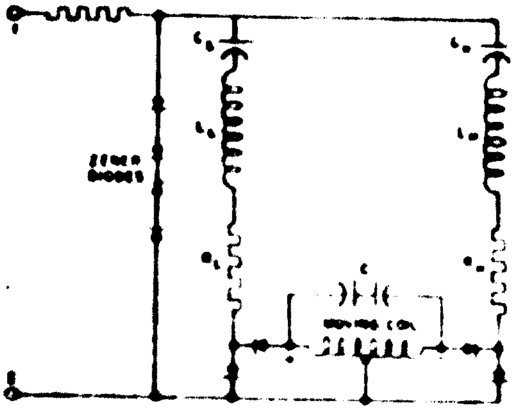


FIG. 26

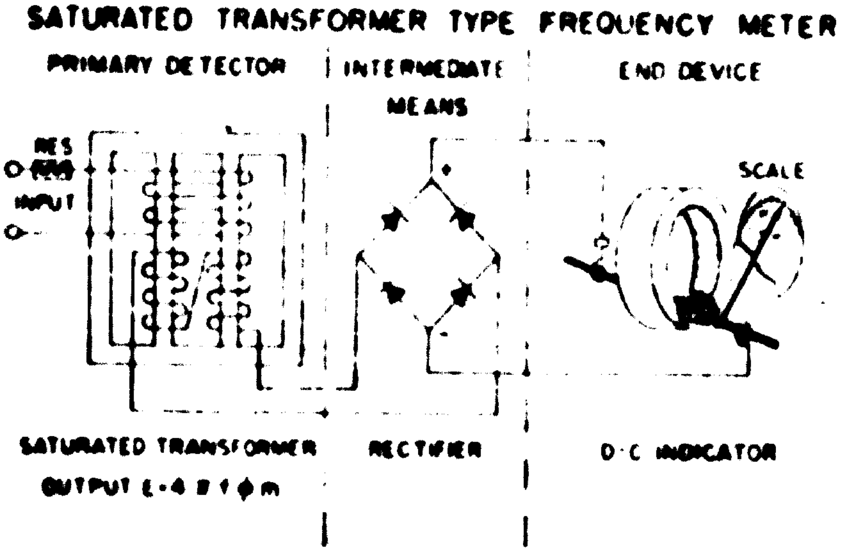


FIG. 27

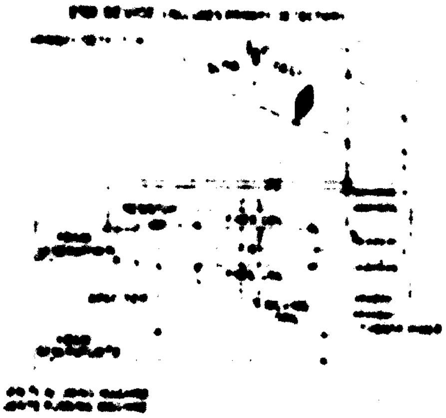


FIG. 28

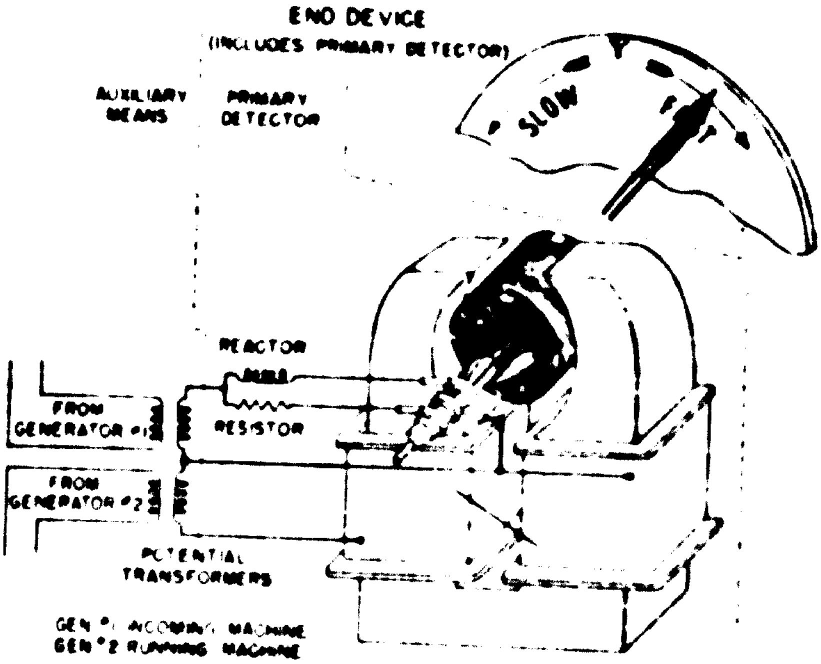

END DEVICE
(INCLUDES PRIMARY DETECTOR)
AUXILIARY MEANS
PRIMARY DETECTOR
SLOW
F
REACTOR
FROM GENERATOR #1
RESISTOR
FROM GENERATOR #2
POTENTIAL TRANSFORMERS
GEN #1 INCOMING MACHINE
GEN #2 RUNNING MACHINE

FIG. 20

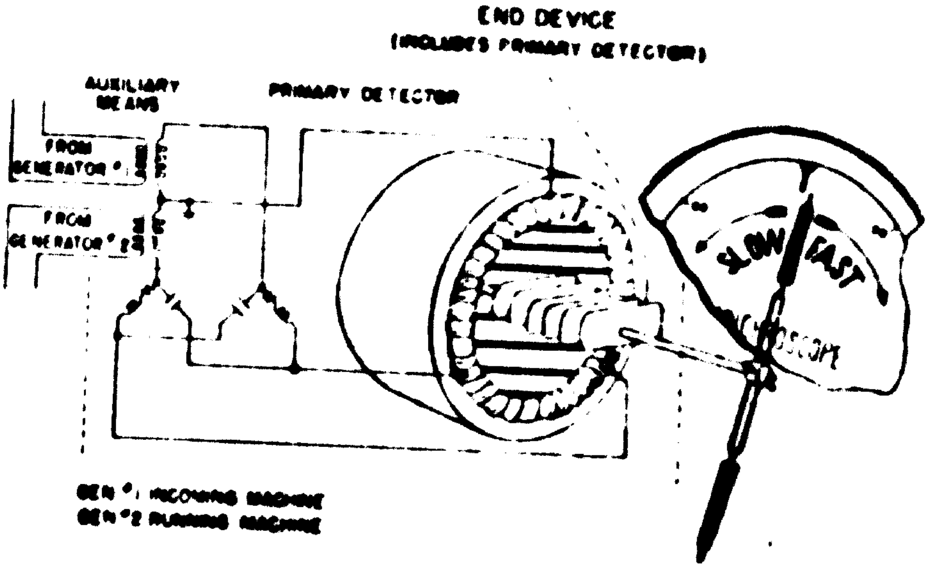

END DEVICE
(INCLUDES PRIMARY DETECTOR)
AUXILIARY MEANS
PRIMARY DETECTOR
FROM GENERATOR #1
FROM GENERATOR #2
SLOW
FAST
SYNCHROSCOPE
GEN #1 INCOMING MACHINE
GEN #2 RUNNING MACHINE

FIG. 21

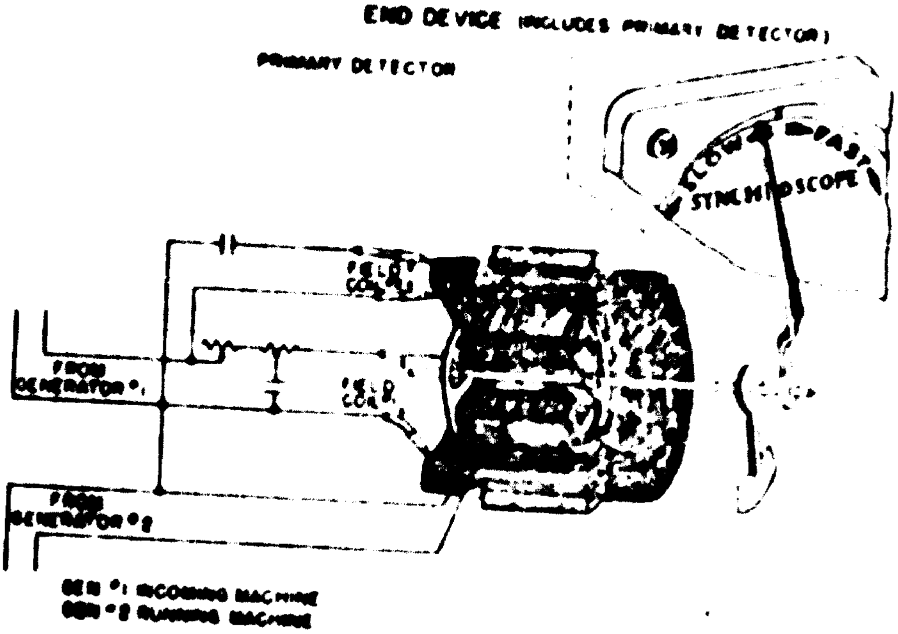
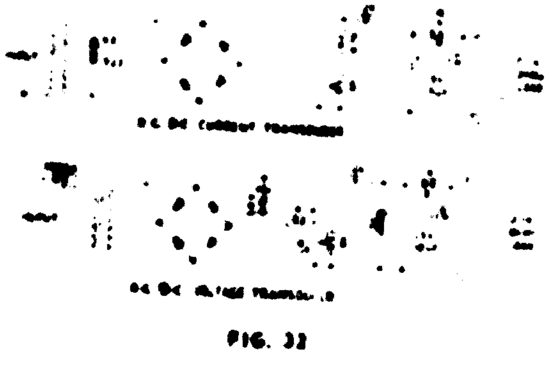


FIG. 31



A-C D-C CURRENT TRANSDUCER

A-C D-C VOLTAGE TRANSDUCER

FIG. 32

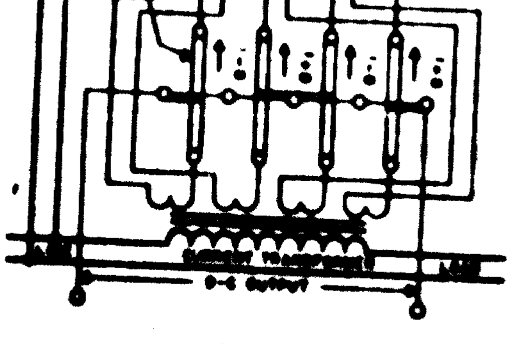


FIG. 33

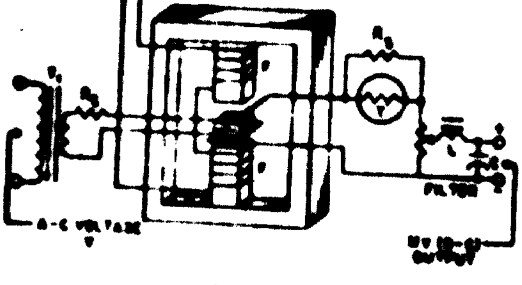


FIG. 34

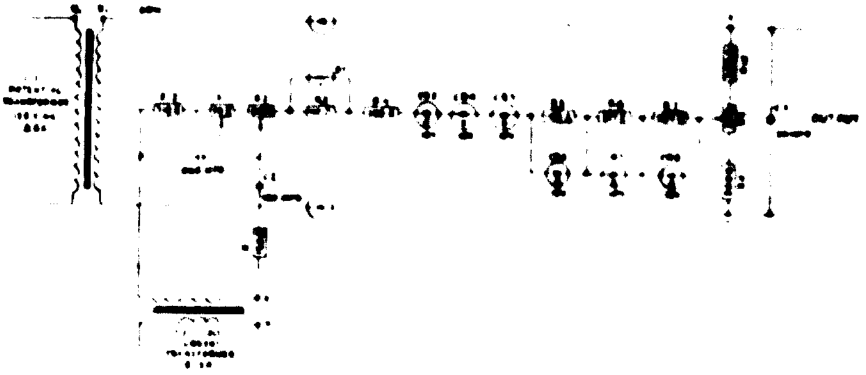
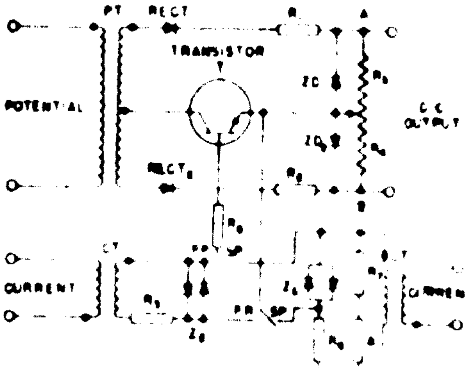


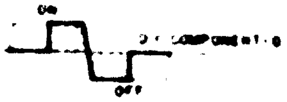
FIG. 35



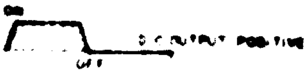
FOR POLYPHASE ONLY (PP) FOR SINGLE PHASE ONLY (SP)

FIG. 36(a)

(a) OUTPUT NO CURRENT NO SWITCHING (CLOSED)



(b) SWITCHING AT 0 P.F. WITH 90 DEG ARTIFICIAL PHASE SHIFT



(c) SWITCHING AT 0 P.F. LEADING

(d) SWITCHING AT 0 P.F. LAGGING

FIG. 36(b)

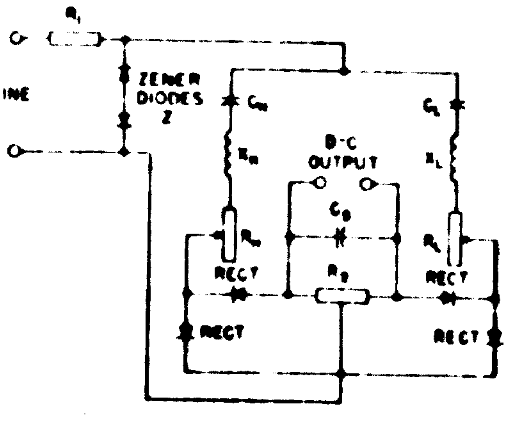
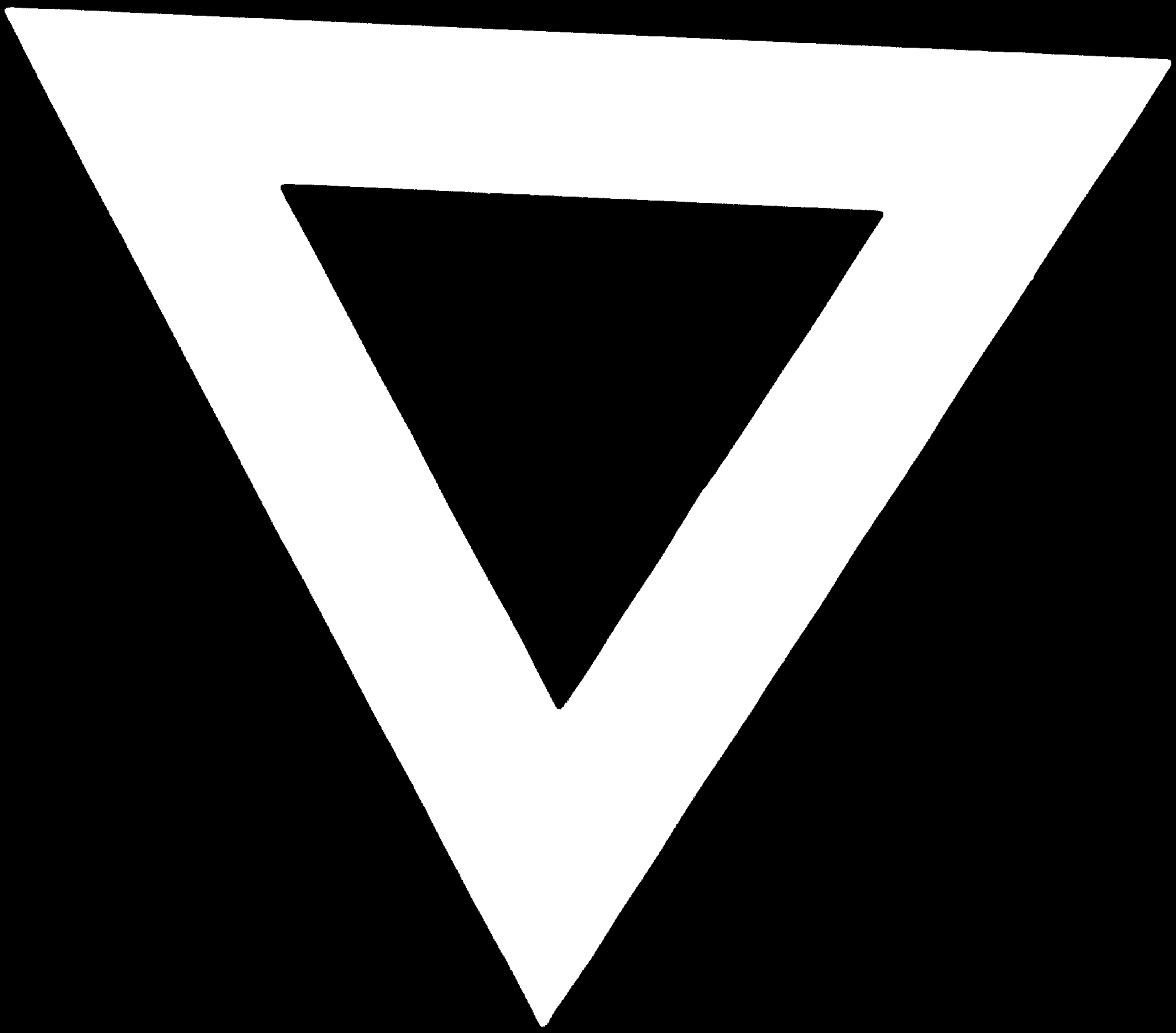


FIG. 37



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