

4.2.3 Using the Square Law Characteristics of Semiconductors

"Square law" instruments are dedicated to the measuring of radio and microwave frequencies at low power levels. They exploit the square law relation between voltage and current in e.g. a diode's transfer curve ($i=u*u$ for small u). They also use the fact that the square of current or voltage over a known impedance according to Ohms law, gives the power

$$P=UI=U^2/Z \quad (69)$$

The signal to be measured, or a fraction thereof, is passed through a diode, or a diode junction, working in the square law region. The output is proportional to the signal power applied to the diode. It is a half cycle rectified signal, smoothed by the inherent capacitance of the diode.

Figure 161 [326] illustrates the principle circuit arrangement.

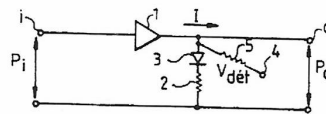


Figure 161 [326]
Diode Signal Power Detector

V_{det} is the power proportional voltage, and the resistor (5) adapts the output impedance.

Diode detectors have a **shorter reaction time**, microseconds instead of seconds, and better sensitivity than thermal or resistive detectors [211] [331]. The problem of temperature dependence can be solved (Fig. 162) [212].

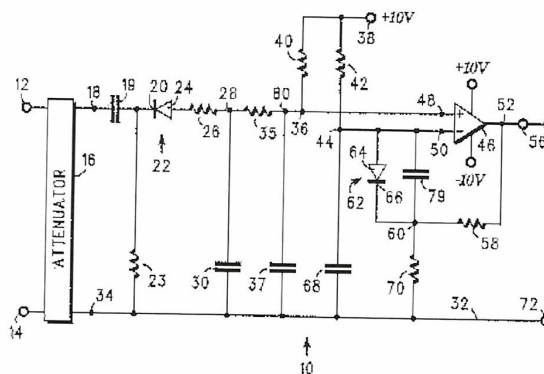


Figure 162 [212]
Temperature Compensated Power Detector

A temperature compensated power detector utilizes a temperature compensating diode connected to an inverting input of an amplifier to enable the amplifier to substantially cancel out undesirable temperature effects caused by a power level detector diode coupled to the non-inverting input of the amplifier. As a result the amplifier output voltage tends to remain constant over temperature in response to a fixed power level being applied to the detector. A lookup table is utilized to determine the power level corresponding to a power detector output voltage of a particular magnitude.

To increase the **dynamic range** when measuring radio-frequency power one can combine thermocouples with diode sensors (Fig. 163) [204].

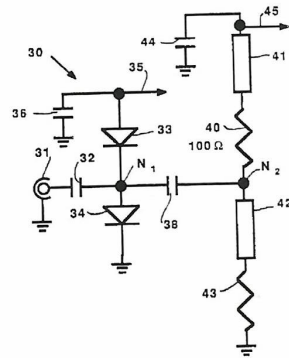


Figure 163 [204]

Wide Dynamic Range Radio-Frequency Power Sensor

A wide dynamic range radio-frequency power sensor (30) having a low-power sensor portion and a high-power sensor portion is described. Both sensing portions are connected to an input signal at the same time without the use of a signal splitter. In the preferred embodiment a single radio-frequency load serves both sensor portions. Each sensor portion has its own output terminal (35-45). The low-power sensor portion comprises a pair of diodes (33-34). The high-power sensor portion (which includes the radio-frequency load) may comprise a pair of diodes preceded by an attenuator (84) or a pair of thermocouples (41-43).

Diodes are the most common devices, but the diode junction in for example a **FET** can be used as well (Fig. 164) [213]. In this circuit the current I_0 is proportional to the power of the signal at "30".

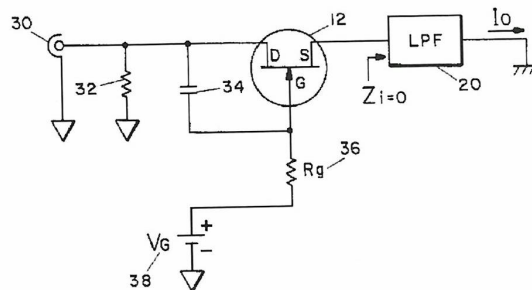


Figure 164 [213]

Broadband RF Power Detector

Measuring of waves in free space is not treated here, but the above methods can be used in conjunction with an antenna for radiation power measurements.

4.2.4 Measuring Current or Voltage,

knowing the impedance

$$P=UI \Leftrightarrow P=U^2/R = RI^2 \quad (70)$$

The "Square law" detectors described above utilize this principle, but it is not limited to high frequency applications. Figure 165 [215] shows a suitably designed measuring scale that translates the linear measurement of voltage to the indication of power. Naturally, the impedance must be known if one wants to display the power in absolute values.

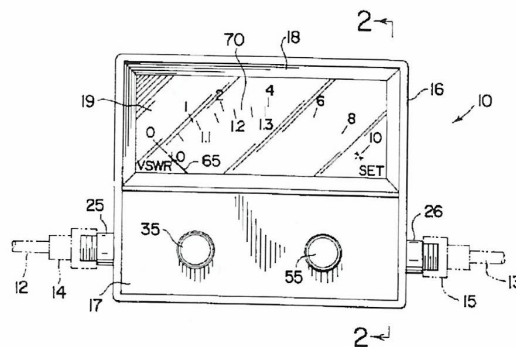


Figure 165 [215]
VSWR Meter Circuit Using Variable RF Attenuator

Measuring the current instead of the voltage with a current transformer and using the transformation formula $P = RI^2$ ($R = 50\Omega$) is being done at radio wave frequencies.

4.2.5 Sensing

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4.2.5 Sensing Current and Voltage separately and multiplying

4.2.5.1 Introduction

Sensing currents and voltages as such is treated in Chapter 1. Sensors of particular importance are: Hall sensors, magneto resistive sensors, inductive and capacitive sensors, shunts, magneto- or electrooptic sensors and current transformers with or without a magnetic core.

Figure 166 [261] shows a simple design using an inductive current sensor and a capacitive voltage sensor.

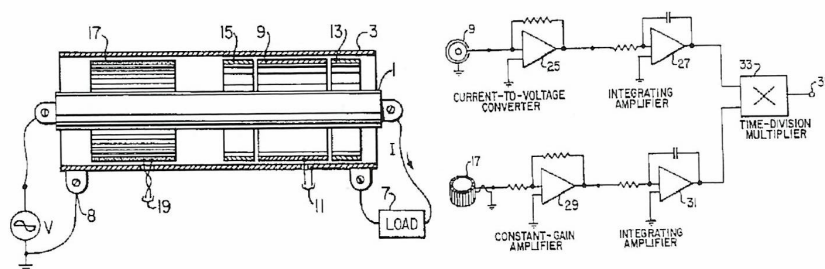


Figure 166 [261]
Voltage and Current Sensing Power Detector

In Figure 167 [333] a thermoelectric sensor measures the effective current, I , which is then multiplied by the effective voltage V and the power factor ϕ to establish the active power P .

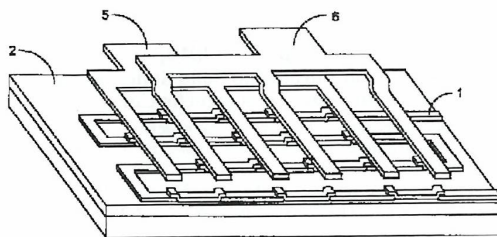


Figure 167 [333]
Thermoelectric Power Sensor

Thermoelectric sensor for measuring true effective current consumed by appliance e.g. water heater or domestic or industrial premises - has resistors for actual and comparison currents in contact with alternate thermocouple junctions in series circuit.

The sensor measures the current by comparing the heat generated by the current in resistor (5) with that from a known comparison current in resistor (6). The resistors are in contact with alternate thermocouple junction in series in a circuit (1). The current difference between the two resistors generates a proportionate EMF i.e. error signal in the circuit due to unequal heating of the thermocouple junctions.

This EMF is amplified and processed by an electronics system which automatically adjusts the comparison current in resistor (6) to cancel the EMF. From the known value of the comparison current, the electricity consumption can be automatically calculated and the value transmitted via an interface to a remote recording point.

ADVANTAGE - Readily miniaturised and produced at low cost by conventional microsystems metal deposition and engraving processes, while increasing reliability.

Hall sensors and magneto resistive sensors are suitable for solid state integration (Fig.146). A possible circuit design is shown in fig. 168 [216]. This design is based on a magneto resistive current sensor, a voltage divider (RC and RD), and a pulse width modulator producing a power proportional output pulse train.

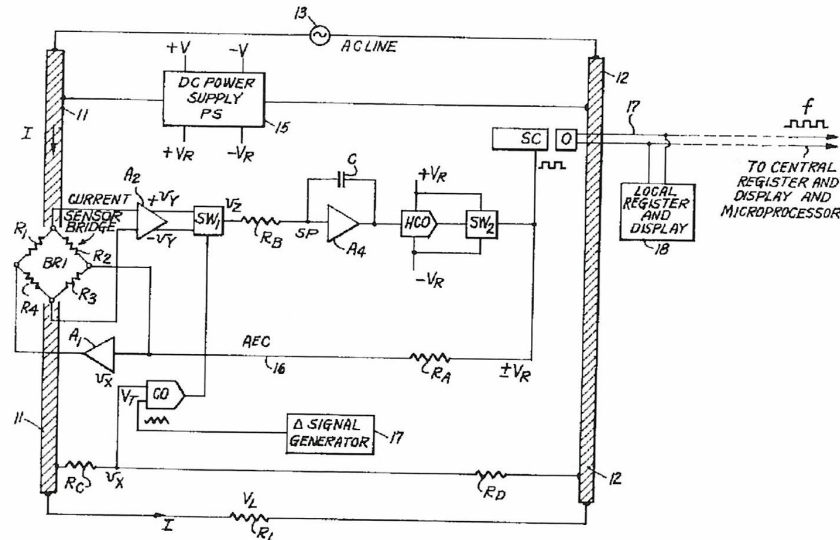


Figure 168 [216]

Low-Cost Self-Contained Transformerless Solid State Electronic Watthour Meter Having Thin Film Ferromagnetic Current Sensor

The low cost, light weight, small size ferromagnetic current sensing device employed in the watthour meter preferably comprises a thin film magnetoresistive magnetic field sensor formed by semiconductor integrated circuit fabrication techniques on a common substrate with other components of the solid state meter circuit. The thin film magnetoresistive magnetic field sensing device preferably is fabricated in the form of a balanced Wheatstone bridge with each arm of the bridge comprising a magnetoresistive magnetic field sensor wherein each field sensor is magnetically coupled to the power supply conductor to be measured. In this arrangement, the two diagonally opposite terminals of the bridge are connected across the input and output terminals of a constant current output amplifier supplied with an input supply current and the two remaining diagonally opposite terminals of the bridge are connected across a set of current indicating input terminals to the multiplier circuit means of the watthour meter. In a preferred embodiment of the invention the watthour meter circuit includes automatic error correction circuit means for feeding back an automatic error correcting polarity reversing signal from the output thereof to the input of the multiplier circuit means for reversing the polarity of one of the input signals to the input of the multiplier circuit means whereby long term errors due to drift, thermal changes and the like are averaged out of the product signals being derived by the multiplier circuit means during each quantizing period operation of the meter.

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With Hall elements, sensing the current and multiplying by the voltage can be done simultaneously (Fig. 169) [217].

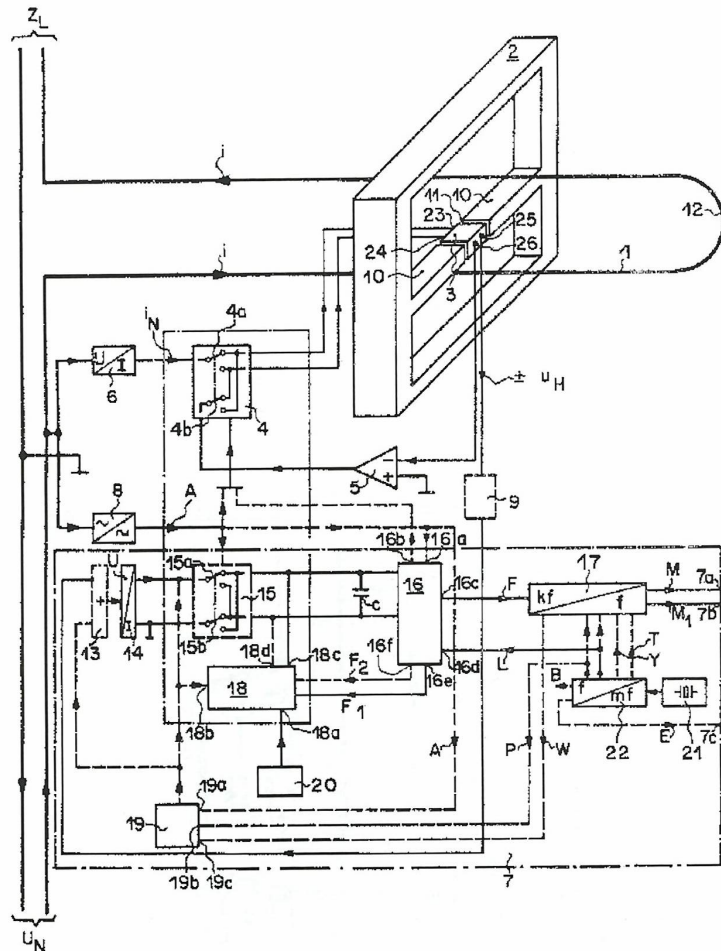


Figure 169 [217]

Electricity consumption meter

A conductor (1) carrying current (i) and a voltage-current converter (6) are provided, the latter converting the supply voltage (U_N) into a current (i_N). The proportional current passes through a Hall effect element (3). The element lies at the centre of a ferromagnetic core in the air gap, lying in the central bar of a figure of eight. The conductor passes through both openings of the core around the Hall element. The output voltage produced by the element is proportional to the product of the current and voltage (i times U_N), and is applied to a voltage frequency converter (7) producing a pulse signal of frequency representing the power consumption.

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4.2.5.2 Analog Multiplication

The commonly used devices are:

- Ferraris wheels, Electrodynamometers and Electrostatic Wattmeters
- Hall elements and Faraday sensors
- Thermo elements
- Solid state multipliers, such as 4 quad. log antilog devices
- Single electronic components e.g. transistors
- Discrete electronic circuits

Ferraris Wheels

The classical electricity meter is based on this device. It is still the most common one in household Watthour meters, because of its comparably low price and reliability. Ferraris type energy meters are also treated in Chapter 5. The torque on the aluminium wheel is proportional to the average AC-power transmitted by the line. A current coil creates Eddy currents in the wheel. These interact with the field set up by the voltage-coil to turn the Ferraris disc (Fig. 170) [218]. The theoretical treatment of the phenomena is complex [297].

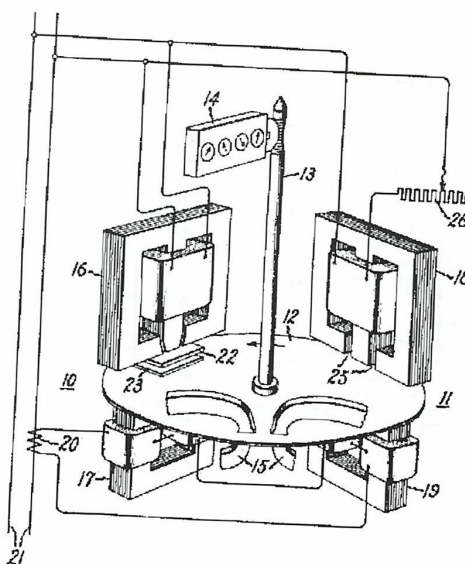


Figure 170 [218]
Volt-Ampere-Hour Meter

The meter torque is the sum of the torques of the two driving elements and remains substantially proportional to volt-amperes over a considerable power factor range. The meter shaft is indicated at 13, the register at 14 and the damping magnets, partially broken away at 15.

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To be noted is that the Ferraris wheel meter does not measure any DC-component. It can be used for DC after an DC-AC conversion by e.g. **transducers**, as in Figure 171 [219].

(A transducer is a DC-AC converter employing a magnetic core. The DC current to be measured constitutes the primary winding. An auxiliary winding on the secondary side is fed by an AC source, periodically reversing the saturation of the core).

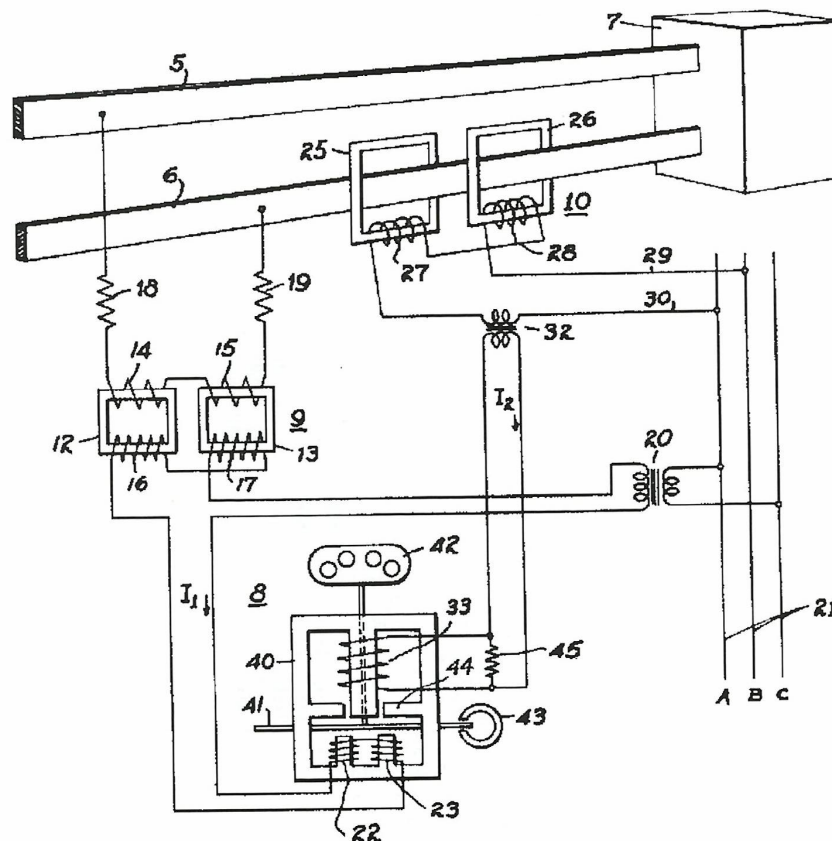


Figure 171 [219]
A Power-Measuring Device

5 and 6 represent the positive and negative line conductors of a D.C. power feeder or distribution bus which, in the case of electrolytic cell or pot line operation for aluminum production, is adapted to carry high current, medium voltage D.C. power supplied from a suitable source indicated at 7. A typical circuit often is designed to carry as much as 100,000 amperes at 600 volts, and needs to be metered with sustained accuracy. To attain this objective, the system of this invention utilizes an induction meter 8, a voltage transducer 9 and a current transducer 10. The two transducers convert the voltage and current quantities of the D.C. power circuit to proportional alternating current quantities. These are then applied to the meter in proper relation to each other in such manner as to effect accurate integration of their product in terms of D.C. kilowatt hours.

A problem with the Ferraris wheel is its non linearity. **Electronic error compensation** using a microcomputer yield good results, but is complicated (extra components). It is shown in Figure 173 [222].

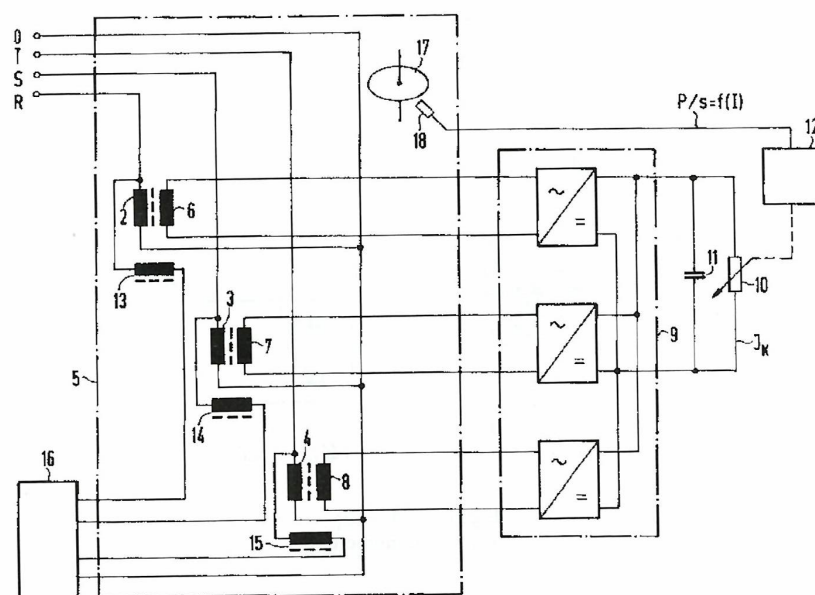


Figure 173 [222]
A Power-Measuring Device

The voltage windings (2-4) of a three-phase wattmeter (5) are provided with auxiliary windings (6-8) wires to a rectifier (9) which supplies compensatory DC to an adjustable resistive load (10) in parallel with a smoothing capacitor (11). The compensation current (I_K) is adjusted by a controller (12) in accordance with the current drawn by a load (16) from the three current windings (13-15). This quantity is measured by a tachometer (18) counting the revolutions of a disc (17), wired to the controller (12), which may be a microcomputer Error compensation circuit in induction wattmeter.

The classical error compensation is performed by an adjustable permanent magnet "15" in Figure 170. Another problem with the Ferraris wheel is its lack of precision. Mechanical parts wear. It does not cope well with certain electrical charge conditions and it is basically only measuring the fundamental frequency component (50/60 Hz).

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Electro dynamometer

If one replaces the permanent magnet in a moving coil instrument (d'Arsonval) with coil(s), i.e. an electromagnet, one gets an electro dynamometer. In Figure 174 [233] (1) and (2) represent current and voltage coils).

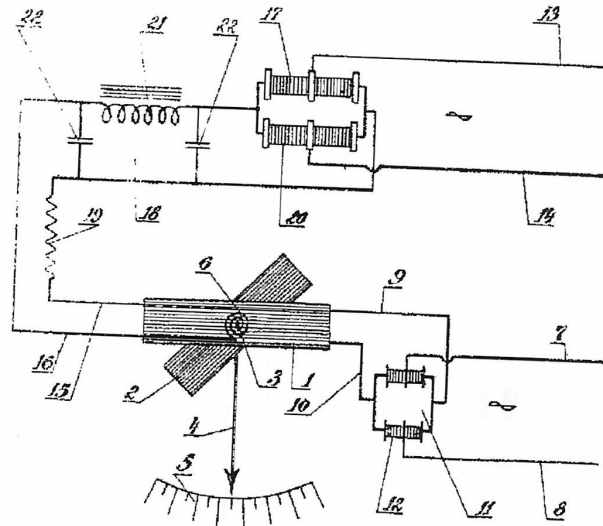


Figure 174 [233]
Electrodynamometer

See also standard textbooks such as [230] or [258], for further details. It is a most commonly used wattmeter. It cannot respond to high frequency signals and is inaccurate at low power factors due to instrument or transformer phase shift. The just cited [233] eliminates the phase problem by rectifying the signals. The meter is a dc instrument. The British National Physics Laboratory has developed one using a microcomputer with an estimated error of 20 ppm [237].

The Electrostatic Wattmeter

This instrument is in theory independent of frequency and power factor. As the name indicates, the instrument is based on electrostatic forces, in a manner similar to the electrostatic voltmeter. Figure 175 [235].

It can be used for AC and DC with the same calibration. Some disadvantages are low torque and vibration sensitivity. [230] describes its function more in detail.

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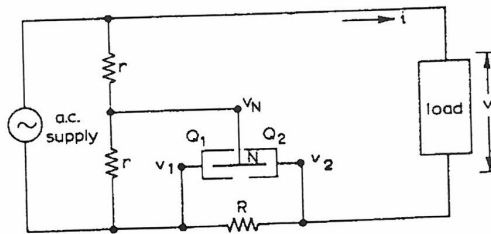


Figure 175 [233]
Quadrant Electrometer used as Wattmeter (incorporating Miles Walker's Compensation for Quadrant-shunt loss)

To use the quadrant electrometer as a wattmeter, a standard resistor called a quadrant shunt is employed in the circuit. The Figure in which R is the quadrant shunt, illustrates a particular case of the well known Miles Walker circuit for power measurement with the quadrant electrometer. In this case, the electrometer is obviously used heterostatically. The expressions for torque is

$$T_{inst} = k(viR)$$

$$\text{or } T_{av} = kR \times (\text{average power in load})$$

[236] describes the use electronics and feedback to overcome some of its disadvantages.
 [237] describes its use in microwave frequencies.

Instead of transforming the current through the voltage and current coil into torque one can let them act as a common core and obtain a "magnetostatic" Watt meter (Fig. 176) [221].

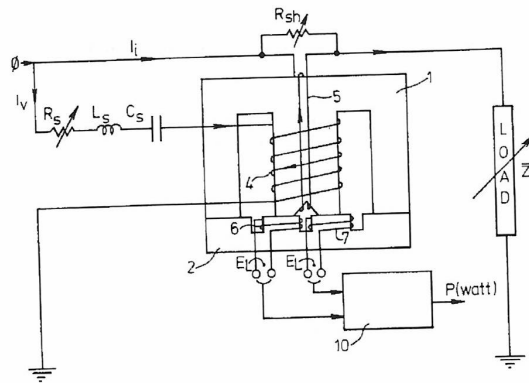


Figure 176 [221]
Magnetostatic Power Meter

HALL ELEMENTS AND FARADAY SENSORS

A Hall element (ch. 1.2.7) senses the magnetic field around a conductor, whether it is an alternating or an invariable field. According to Ampere's law (in its special version) the line integral of the field is proportional to the current:

$$\mu_0 I = \oint \mathbf{B} ds = 2\pi r B \phi = \mu_0 I \quad (72)$$

for a long straight conductor.

I = current in the in circled conductor (A)

$\mathbf{B}$ = Magnetic field (T)

ds = line segment (m)

$\oint$ = line integral

μ_0 = permeability in vacuum (Vs/Am)

r = radius (m)

B = circular magnetic field (T)

Cf. section 1.2.1, p. 29-31

Compared with a normal current transformer, that only can measure AC, a Hall element is a small device.

Hall elements are being used as current sensors in power measuring devices. An interesting feature is that they can act as multipliers. As explained in chapter 1.2.7 the output signal from a Hall element is proportional to the magnetic field across it, which in its turn is proportional to the current in the conductor to be measured, and to the current feeding the Hall element.

If we then feed the Hall element with a current proportional to the voltage in the conductor to be measured, we obtain an output proportional to the power supplied by the conductor ($U \times I$)

In Figure 179 (18) is a Hall element being used in this way. (19) detects the output voltage, i.e. the power to be measured.

Typical **problems** to solve are long term stability, sensitivity to interfering fields, low sensitivity and low signal to noise ratio.

In order to increase the sensitivity a magnetic circuit such as a circular iron core can be used for concentrating the flux. The Hall element is then placed in an air-gap in the core (Figs. 177 [224] and 178 B [225]).

An improvement of this construction consist in reducing the section of the magnetic circuit adjacent to the air-gap. This concentrates the flux over the Hall element and thus improves the sensitivity (Fig. 177) [224].

Cf. p. 30-31

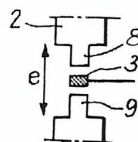


Figure 177 [224]
Flux Concentrator

Current transformer for continuous, alternating or pulsed currents. In the vicinity of the air-gap, the magnetic circuit (2) has at least one portion with reduced section.

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A problem in using iron cores is that it has a non-linear magnetization (B-H) curve, as seen in Figure 178 A [225]. The levelling out of the curve for high values of the field strength (H) is caused by saturation of the iron core. The saturation starts at the inner radius of the core and gradually works its way outwards.

By giving the core a shape with a big difference between inner and outer radius, we can achieve an almost linear B-H curve.

The difference in circumference between inner and outer circumference should be at least 3 times, and preferably 5. See Figure 178 B [225].

The air-gap does not have to be in the circumferential direction. See Figure 178 C.

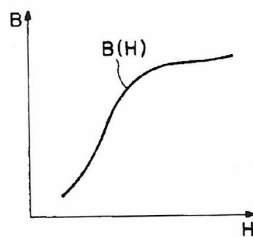


Figure 178 A [225]

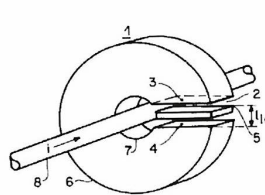


Figure 178 B [225]

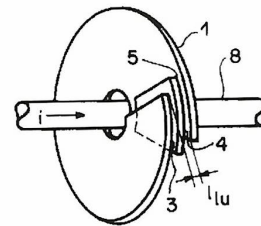


Figure 178 C [225]

Iron Cores with Improved Magnetization Curves

An additional advantage of the device in Figure 178 is that the Hall element is shielded against interfering fields by the iron core.

Offset voltage can be corrected by using a second Hall element (Fig. 179) [226].

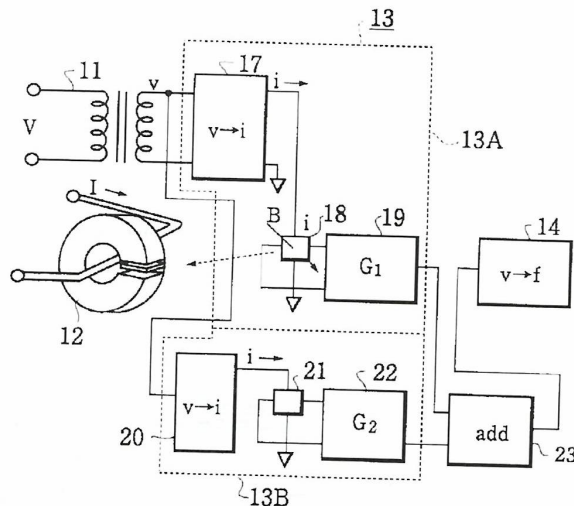


Figure 179 [226]
Electronic Watthour Meter

A first Hall element (18) is supplied with a current proportional to a load voltage and applied with a magnetic field proportional to a load current and produces a voltage proportional to a load power given by the load voltage and the load current. A second Hall element (21) has the same characteristic as that of the first Hall element and supplied with the current proportional to the load voltage and no magnetic field. The output voltages of the first and the second Hall element are combined by combining means (23) to compensate and remove an offset voltage component contained in the output voltage of the first Hall element.

Hall elements are suited for solid state manufacturing technics. Figure 180 [227] shows details of a design.

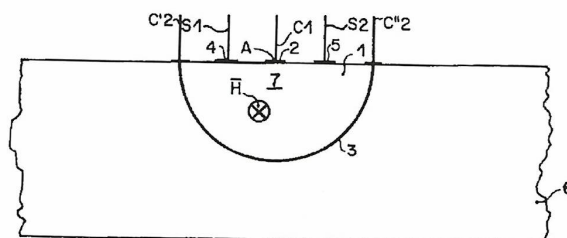


Figure 180 [227]
Integrated Hall Element for Electricity Meter

The Hall element has a semiconductor layer (6) of a single conductivity type carrying two sensor electrodes (4,5) and a current electrode (2). The current electrode lies between the sensor electrodes (4,5) along the centre line between them. An additional current electrode (3) with a semicircular cross-section ensures a vectorial sum current which is perpendicular to the surface of the semiconductor layer (6) adjacent the first current electrode (2). Pref. the second current electrode (3) has its axis symmetrical to a line through the first current electrode (2) normal to the semiconductor surface.

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Faraday elements are, as Hall elements, sensitive to the magnetic field. A power measuring set-up can be carried out by arranging a Faraday element as a current sensor (Ch. 2.2) and modulate the light emitting element with the unknown voltage.

One then obtain a power sensor not requiring any current transformer. See Figure 181 [320].

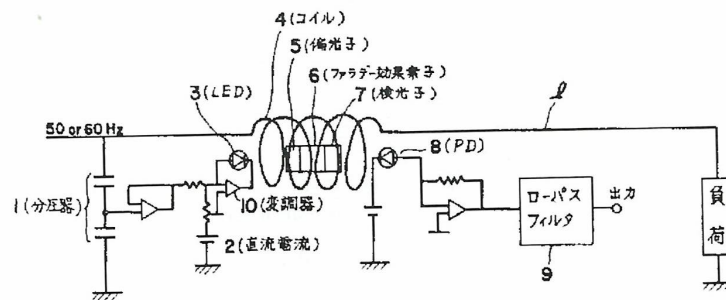


Figure 181 [320]
Power Sensor Comprising a Faraday Cell

PURPOSE: To achieve a smaller size and a lighter weight of the apparatus, by a method wherein a modulation is applied to a light emitting element by a voltage at a measuring point and light thus obtained is passed through a Faraday effect element subjected to a modulation by a current at the measuring point to form a power sensor requiring no current transformer.

CONSTITUTION: A light emitting element LED 3 is driven with a DC power source 2. As the element is controlled with a modulator 10 with the application of a voltage of a capacitor voltage divider 1 thereto, emission of the LED 3 is turned to a light modulated by a voltage signal. The light modulated generates a Faraday effect in a coil 4 by a magnetic field with a current flowing to the coil 4 through a Faraday effect element 6 placed between a polarizer 5 and an analyser 7 to cause a modulation of light. Light emitted from the analyser 7 is received with a photo diode PD8 to be converted into electricity which is passed through a low pass filter 9. Thus, with the removal of an AC component, a DC component is determined to be measured with a voltmeter.

Thermal converters

These are small, robust, stable in time and have a large frequency range. **Thermocouples** are basically squaring elements, see Chapter 4.2.2.1 above, but connecting two of them together gives a “**sum and difference multiplier**”, an averaging multiplier, Figure 182 [228] shows a circuit design for a thermal Watt meter. The mathematics behind it are:

$$V_{dc} = k / T \int_0^T ((u+i)^2 - (u-i)^2) dt = k / T \int_0^T 4uidt \quad (73)$$

where T stands for time and k is a constant.

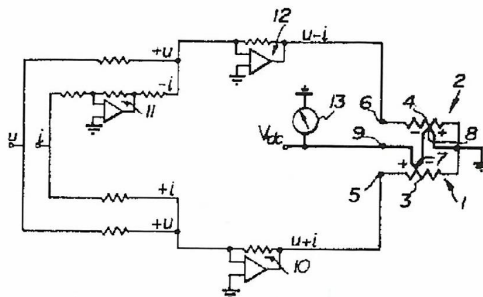


Figure 182 [228]
Differential Thermal Wattmeter

The resistor 4 is heated by a current proportional to $u-i$, and the resistor 3 by a current proportional to $u+i$. This gives us the two heat quantities

$$\delta Q(u-i) = R(u-i)^2 dt \text{ and } Q(u+i) = R(u+i)^2 dt \text{ (Joule's law)} \quad (74)$$

In comparison with e.g. electro dynamometers, another type of averaging wattmeter, thermal multipliers have a large error (short term instability, low output voltage). They are however small and portable, insensitive to shock, vibration and attitude [229]. They are used in audio-frequency range, and are good for very distorted wave forms.

The zero instability can be eliminated by automatic reversing [230]. This reference describes a Watt meter with a linear scale, a resolution of 10 ppm and a direct reading accuracy of 30 ppm in the 50-1000 HZ range.

The problem of the non-quadratic and non-identical response of the thermal converters is solved by DC feedback and input interchanges in the already mentioned [228] (Fig. 183).

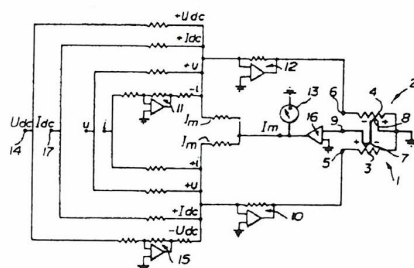
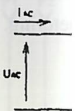


Figure 183 [228]
Wattmeter

A differential thermal wattmeter of the type disclosed in U.S. Pat. No. 4,045,734 is modified to remove undesirable in-phase a.c. ripple at the fundamental frequency in the feedback path. This result is achieved by a closed loop system in which the in-phase signal in the feedback path is detected and driven to zero by injecting sufficient signal in opposite polarity into the feedback path to cancel the ripple. The advantages are reduction of error and the ability to use standard, low cost components.

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With digital sampling technique and a **desktop computer** it is possible to achieve a system with reduced transfer error (accuracy better than 30 ppm at line frequency and all power factors) up to 10 KHz (Fig. 184) [232].

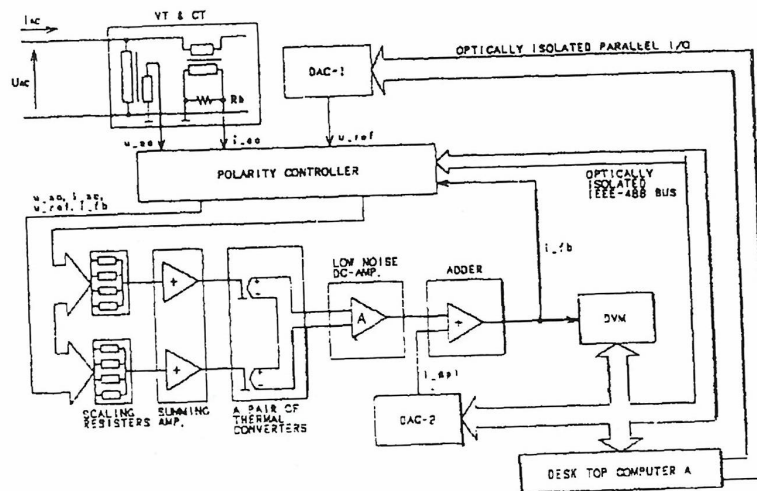


Figure 184 [232] ©1991 IEEE
Block Diagram of the Precision Thermal Wattmeter

[230] describes a thermal instrument for precision measurement of AC voltage, current, power and energy of power frequencies. It has a 0.001% of full scale error for power measurements, and uses digital circuits. The accuracy of this instrument relies on a continuous ac/dc transfer.

Electronic Multipliers

Multiplying circuits in general are beyond the scope of this book. For a treatment of analog multipliers, we refer to "Analog Integrated Circuit Design", Chapter 7 [238]. A problem related to multipliers in power measuring is that it is difficult to reach a high precision (1%).

Figure 185 [239] shows an example of using analog four quad multipliers in three phase metering.

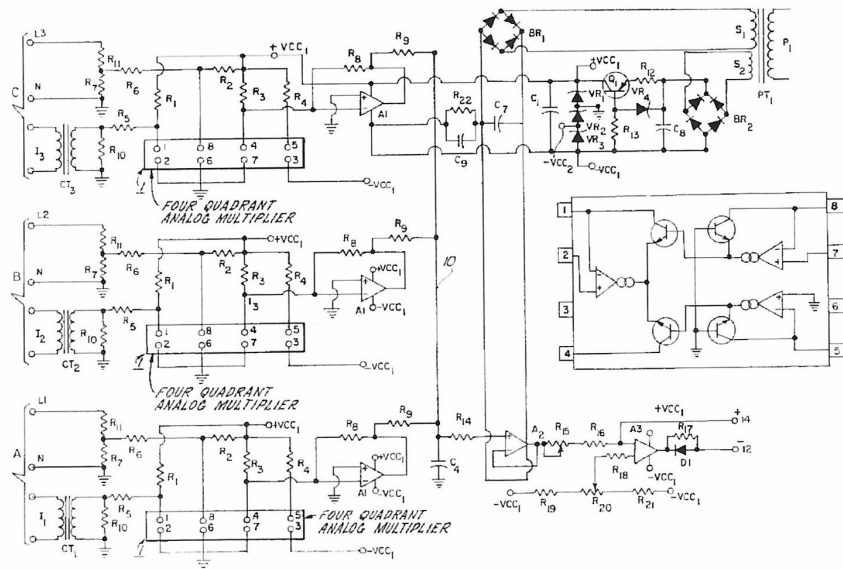


Figure 185 [239]
Alternating Current Watt Transducer

An alternating current watt transducer including an integrated circuit analog multiplier, providing four quadrant multiplication, to the input terminals of which are applied alternating current signals proportional to the voltage and current determinative of the watts to be measured. The integrated circuit analog multiplier provides an alternating current output signal which being proportional to the product of the in-phase components of the input signals, is proportional to the watts being measured. The alternating current signal which is proportional to watts is transformed to a constant-current direct current output.

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Figure 186 [240] demonstrates an electronic Wattmeter with a dedicated multiplying circuit

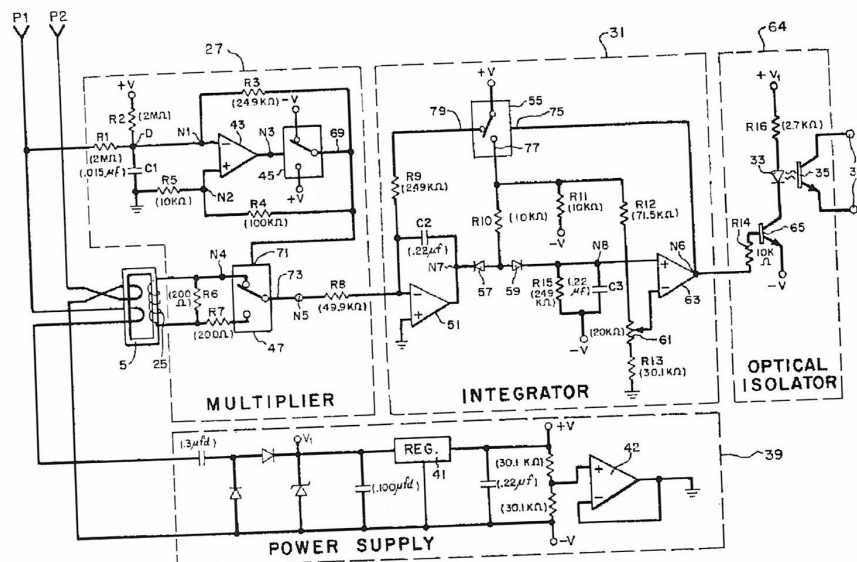


Figure 186 [240]
Electronic Wattmeter

Current and voltage of power lines are monitored and used to generate unitized voltage pulses at a frequency that is proportional to the average power carried by the lines. The current transducer is inductively coupled to the monitored power lines and includes a magnetically permeable frame which has two magnetically permeable, spaced parallel leg members and a magnetically permeable cross-member that is detachably affixed between the leg members. The monitored power lines pass through an aperture defined by the leg members and cross-member of the frame and the frame additively applies the magnetic fields of the conductors to a coil that is inductively coupled to the frame. The coil generates an induced current corresponding to the current of the conductors. A multiplier samples the induced current at a rate defined by the line voltage and generates an output voltage signal that has an average intensity that is representative of the product of the line voltage and the current of the lines. An integrator successively integrates the output voltage signal of the multiplier to a particular magnitude and generates a unitized pulse for each integration up to the particular magnitude. An optical isolator generates an output signal that is modulated by the unitized pulses of the integrator and that is electrically isolated from the line voltage of the power lines.

Log-antilog devices make good multiplication circuits for electric power calculation (Fig. 187) [242].

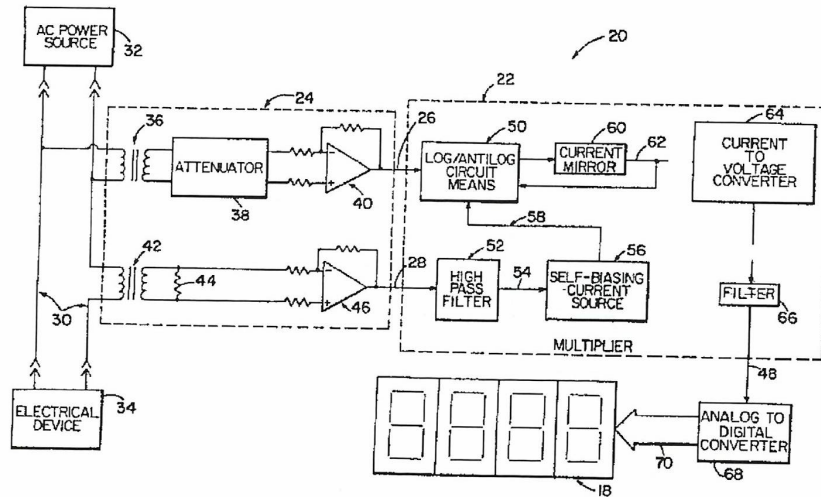


Figure 187 [242]
Power Measuring Apparatus

Single components can be used as multipliers. Figure 188 [245] illustrates a minimalistic multiplier based on a single transistor.

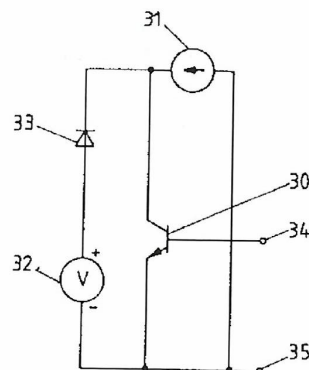


Figure 188 [245]
Multiplier Circuit

The products of the current (31) and the voltage (32) determines the heating of the transistor (30). The heat dependent emitter-base voltage constitutes the output.

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37) [242].

An oscilloscope makes a simple multiplier (Fig. 189) [243]. Here the horizontal deflection is driven by a current-proportional signal, and the vertical deflection by a voltage-proportional one. The mapped area is proportional to the power delivered to the load under study.

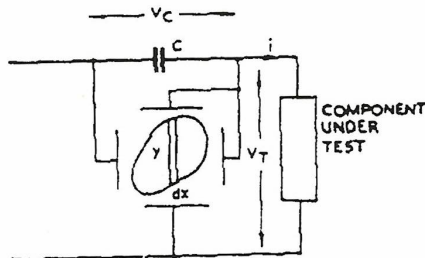


Figure 189 [243]
High Speed Power Analyzer

4.2.5.3 Digital Multiplication

It is not our intention to cover general electronics, but we will give some examples of digital multiplication in watt meters:

Figure 190 [244] gives a schematic overview of the use of a microprocessor for multiplication and linearization.

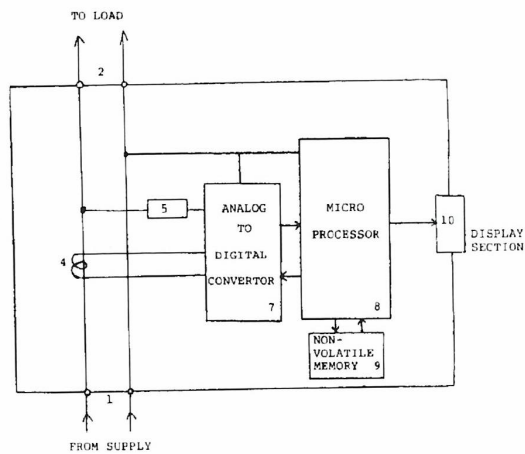


Figure 190 [244]
Improvements in and Relating to Electricity Meters using Current Transformers

Sampling is of particular concern.

The ADC is often of a fast type in order to avoid errors due to un-equal sampling of current and voltage, and in order to capture the true wave forms (Fig. 191) [245]. (Cf. ch. 4.1.1)

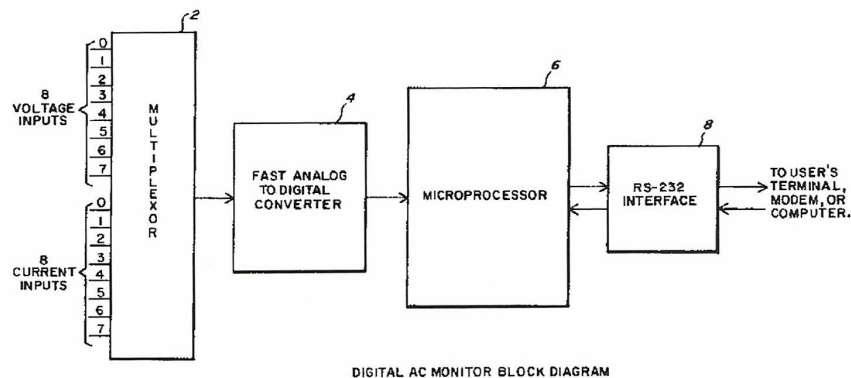


Figure 191 [245]
Digital AC Monitor

An apparatus and method is provided for monitoring a plurality of analog ac circuits by sampling the voltage and current waveform in each circuit at predetermined intervals, converting the analog current and voltage samples to digital format, storing the digitized current and voltage samples and using the stored digitized current and voltage samples to calculate a variety of electrical parameters; some of which are derived from the stored samples. The non-derived quantities are repeatedly calculated and stored over many separate cycles then averaged. The derived quantities are then calculated at the end of an averaging period. This produces a more accurate reading, especially when averaging over a period in which the power varies over a wide dynamic range. Frequency is measured by timing three cycles of the voltage waveform using the upward zero crossover point as a starting point for a digital timer.

Depending on the use of the power measuring apparatus, the requirements on the sampling are different: **Protective circuit breakers** need only a few data points, but require rapid results. **Metering** calculations, on the other hand, do not have to be performed rapidly, but require many sampling points, especially if the signal to be measured is rich in harmonics.

The apparatus is a single device. See 1



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The apparatus of [321] uses **equivalent sampling** to combine the needs of protection and metering in a single device, and with a minimum of computational power. It includes a single standard microprocessor. See Figure 192 [321].

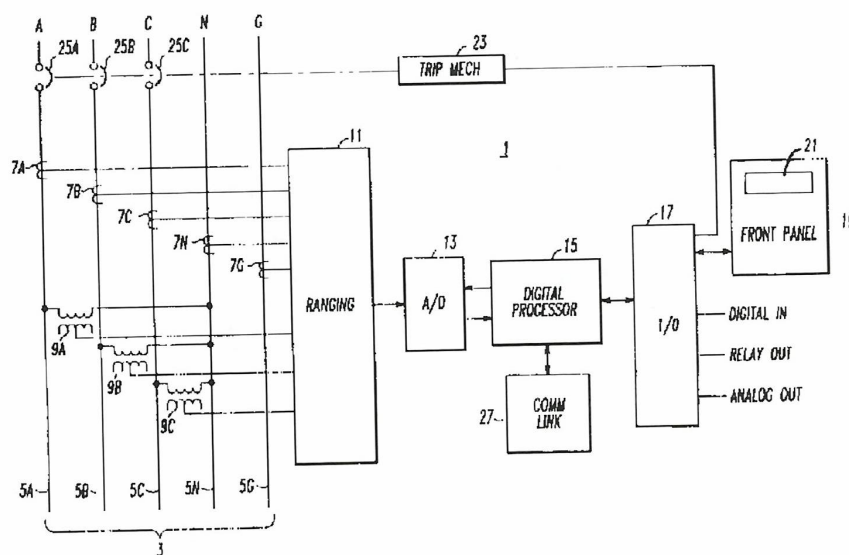


Figure 192 [321]
Equivalent Sampling Power Meter

A circuit interrupter (1) samples waveforms in a protected circuit (3) by taking samples in pairs (P1, P2) spaced 90 electrical degrees apart. The sum of the squares (S2) of samples in each pair, which is representative of the RMS value of the fundamental frequency of the waveform, is used for instantaneous protection (55) by comparing a running sum (S4) of the squares for the two most recent pairs of samples to a threshold representative of the instantaneous trip pick-up value. This sum of the squares (S4) of successive two pairs of samples is also used for short delay protection (61). A delay between successive pairs of samples is varied to produce a selected equivalent sampling rate after a given number of samples. Samples accumulated at this equivalent sampling rate, which is sixty-four samples per cycle in the preferred embodiment, are used for long delay protection (69) and metering.

It is difficult to obtain **simultaneous current and voltage values**.

Elaborate sampling schemes enable the use of a slower, and cheaper, ADC without losing in precision, given that the signal is reasonably smooth.

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A classical method for minimizing the error due to non-identical sampling instants is to periodically reverse the order of the respective voltage and current samples, so that they alternate in leading and lagging every second time, i.e. $p_1 = u_1 i_2$, $p_2 = u_2 i_1$, $p_3 = u_3 i_4$ etcetera. See Figure 193 [322]. The power samples p_i are in this device averaged over a great number of samples: $p = 1/n(u_0 i_1 + u_2 i_1 + \dots)$.

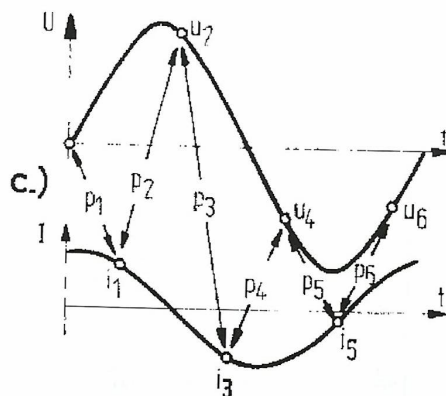


Figure 193 [322]
Sampling Scheme

An alternative is to use interpolation of one of the current/voltage values to the sample instant. See Figure 194 [322].

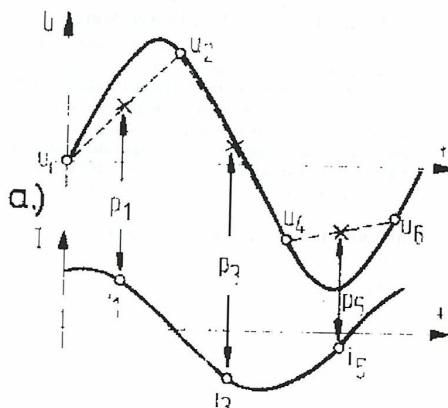


Figure 194 [322]
Sampling Scheme

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A simplified sampling scheme reduce the need for computational power, and enables the use of a single processor for measuring, calculating power and performing additional tasks such as controlling a process. [323] illustrates how this can be done. The device applies a correction for the error resulting from the time lag between current and voltage sample: Correction factor= $1/\cos(\pi/2 f T)$. This factor is deduced by considering that the time lag T between samples has the effect of phase shifting the current and voltage curves. See Figure 195 [323].

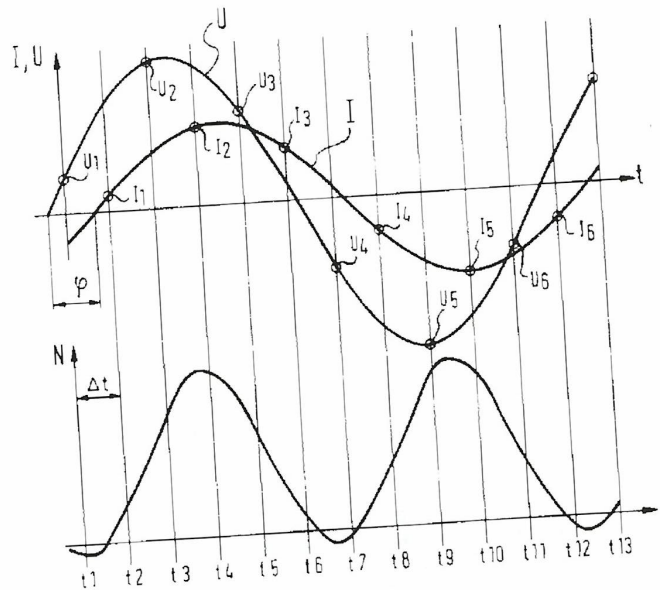


**Figure 195 [323]
Sampling Scheme**

In a method for measuring the consumption of electrical energy by a consumer the momentary values of the alternating voltage and alternating current are measured alternately in the time periods of a sampling cycle. Each measured momentary value is stored. From the momentary value measured in each sampling period and the stored momentary value the product is formed and the formed products added together. The sum of the products formed is then multiplied by a correction constant depending on the frequency of the alternating current and of the alternating voltage as well as on the sampling period.

ADVANTAGE - Reduces time required for measurement. Since previously microprocessor required complete sampling period to obtain momentary energy consumption and second microprocessor was needed for control procedures, single microprocessor can now perform both measurement and other tasks.

Each of E , I and α can also be separately determined [248], or sampled more or less simultaneously. The series of samples $p_1, p_2, p_3 \dots$ (where $p_i = u_i i_i \cos \alpha_i$) are then averaged over for example one half period, as in [249]. This is a common method (Fig. 196).

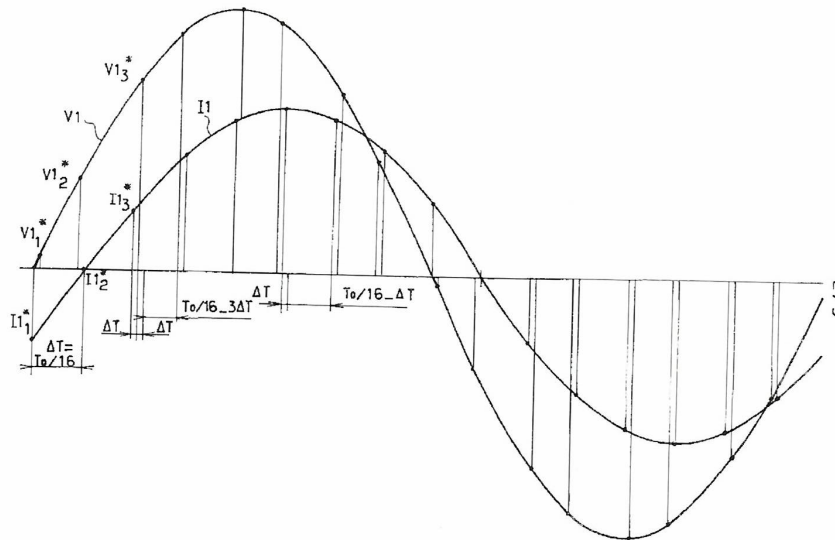


Figure 196 [249]
Process and Device for Measuring Electric Power

A method for measuring the electrical power on an alternative current network, wherein samples taken at different time points and representative of the various network electrical magnitudes related to the power or to each power to be measured are transmitted to a computing device through a single channel, characterized in that, over a determined time period which is equal to or a multiple of the network half-period, sample groups are respectively taken which comprise groups of a first kind each including at least one couple formed by voltage and current samples related to a desired power and taken in a determined order and with a determined time interval, and groups of a second kind in the same number as the groups of the first kind and each including at least one couple of samples of the same voltage and current as said couples in the groups of the first kind, taken with the same time interval but in a reverse order to said determined order, each group of both kinds comprising samples which are all taken at different times, the distribution of the sampling times of the first kind groups and the distribution of the sampling times of the second kind groups being symmetrical to one another relative to the middle of the sampling period and, in that the individual powers obtained by multiplying with one another the samples from the couples of the various groups are cumulated.

[196]. Figure 146 uses exponential averaging of the instantaneous power values to reduce the error induced by sampling voltage and current at different instants.

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Pulse width modulation is commonly being used in multiplying currents and voltage values (Fig. 197) [247]. A popular modulation technique is let one input variable, e.g. the voltage, modulate the pulse width, and to let the other variable, i.e. the current, modulate the pulse height.

The resulting digital signal - proportional to power - can easily be exploited to elaborate e.g. average power value by low pass filtering.

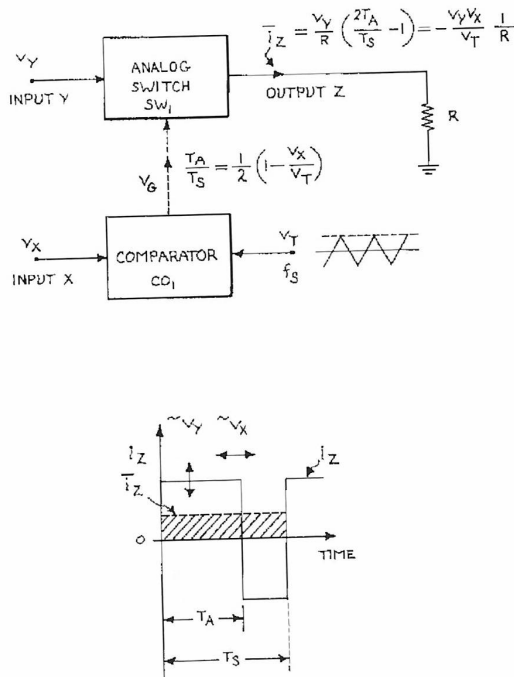


Figure 197 [247]

Electronic Watt Transducer Circuit with Constant DC Current Output Proportional to Watts

An electronic wattmeter in the form of an electronic watt-transducer circuit requiring a minimum number of components that can be fabricated by monolithic semiconductor integrated circuit manufacturing techniques and which provides a direct current output signal that is proportional to watts. The electronic watt transducer circuit comprises a first transformer for developing a first voltage related signal proportional to the input voltage to be measured and a second current transformer for developing a second current related signal proportional to the input current to be measured. A pulse width modulator is connected to receive the first voltage related signal and an input repetitive sampling signal for producing repetitive pulse width modulated output pulses having instantaneous pulse width proportional to the corresponding instantaneous amplitude of the first voltage related signal. Double-pole, double-throw electronic switch multipliers are connected to be automatically switched in response to the repetitive pulse width modulated output signal to develop at the output thereof alternating polarity, pulse width and amplitude modulated signal pulses having instantaneous pulse widths proportional to the first voltage related signal and instantaneous amplitudes proportional to the second current related signal, and a DC component proportional to the product of the two and hence to the power consumption represented by the electric voltage and current being monitored. An averaging type current-to-current converter is connected to the output from the electronic switch multiplier for providing an output analog average direct current electric signal proportional to watts.

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A summing arrangement which employs $\Sigma\Delta$ modulation which is suitable for integration on a single chip is illustrated in Figure 198 [324]. This relatively simple arrangement yield sufficient accuracy and dynamic compared to the ones using classic multiplication. "3" denotes a multiplier/adder stage.

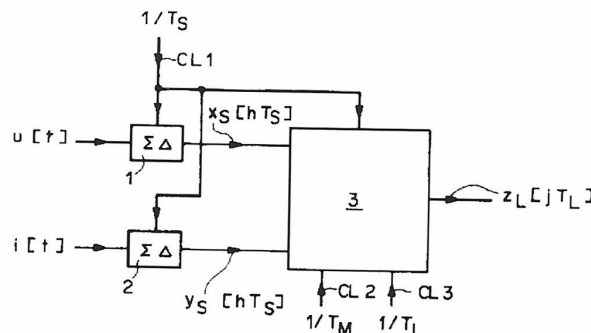


Figure 198 [324]
Integrated Power Measuring Arrangement

Two functions (u , i) of time are input to respective sigma-delta modulators (1, 2) clocked at a first frequency ($1/T_S$). The outputs (x_S , y_S) pass to a multiplier/adder (3) clocked at the same and two further frequencies ($1/T_M$, $1/T_L$). Both modulators are pref. of second order and the multiplier/adder comprises two decimation filters, a delay stage (with opt. a decimation-less digital sliding filter), an addn. element and a divide-by- N (over-sampling rate) element.

USE / ADVANTAGE - In e.g. Watt-hour meters for RMS current or voltage values, correlations or averaged powers, the computation requires no multiplication of two R-bit operands, but only simple shifts and algebraic additions. Maintains precision achievable in conventional multiplication by use of clocked sigma-delta modulators and triply clocked multiplier-adder.

Measuring a plurality of quantities

The versatility of **microcomputers** make them the ideal component for integrating in instruments capable of extracting a multitude of information from the input signals (see Figures 199 [248] and 200 [325]).

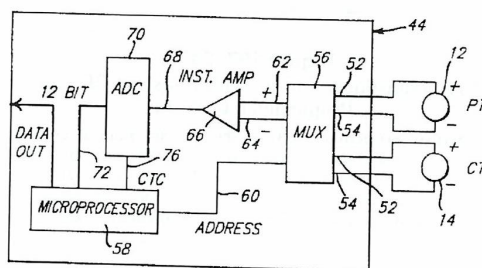


Figure 199 [248]
High Speed Power Analyzer

A method and apparatus for rapidly and continuously sampling AC voltage and current signals in a plurality of power distribution circuits. The sampled signals are then analyzed in a sine board computer to derive the number of fundamental electrical variables. These variables include frequency, RMS volts, RMS amps and a phase angular relationship between the voltage and currents in the system. The computer also performs calibration and compensation functions. From these fundamental variables, other useful parameters can be calculated such as watts, watt-hour, VARS, and power factor.

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4.3 COMPONENTS OF POWER

As in all fields of technology, we see an increased use of distributed intelligence in power metering apparatus. Figure 200 [325] illustrates the front panel forming the user interface of a power system monitor. It presents the operator with a large number of parameters.

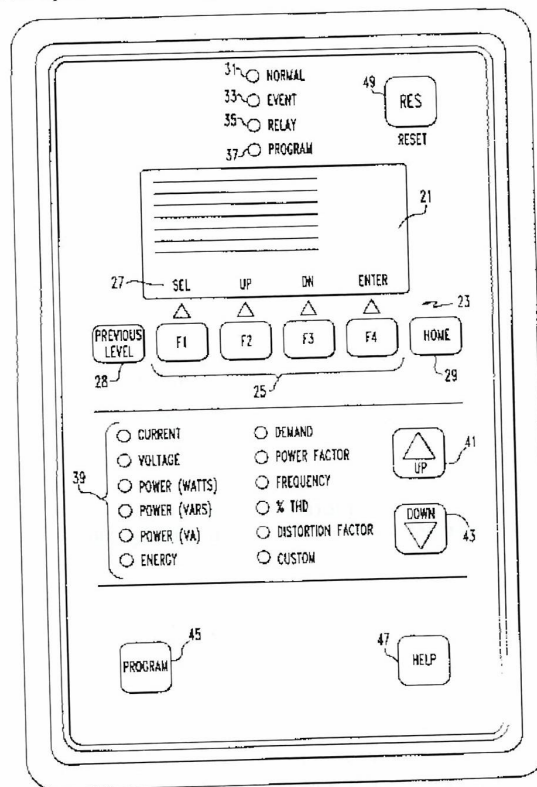


**Figure 200 [325]
Front Panel for Power System Monitor**

Apparatus for monitoring electrical parameters in an electrical system includes a display on which values of the various monitored electrical parameters are displayed, several at a time. The apparatus can be programmed to generate a custom display presenting selected ones of the many parameters, such as the ones most often referenced by the operator, so that it is not necessary to scroll through the large number of parameters to find those of frequent interest.

A selector is used for selecting the custom set of electrical parameter values for display on the display device the preset number at a time. The custom set includes a number of electrical parameter values which is greater than the preset number of electrical parameter values, and the selector includes a device for sequentially displaying portions of the custom set of electrical parameter values the preset number at a time.

- USE/ADVANTAGE - E.g. for metering systems, and for analysis of parameters such as current, voltage, power, energy, VARs, power factor frequency, harmonic distortion etc. Can also be used to evaluate circuit breakers, or to contactor or motor starter. Allows operator to quickly view values of selected parameters without it being necessary to scroll through large number of parameters to find those of frequent interest.

The complete system is illustrated by Figure 201 [325].

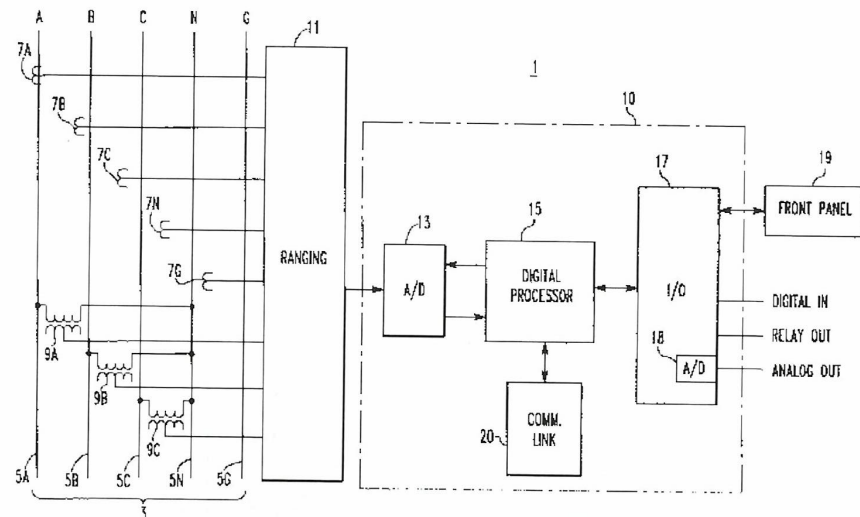


Figure 201 [325]
System Diagram Corresponding to fig. 200

The apparatus for monitoring an electrical system, comprises a device for sensing a number of waveforms in the electrical system. A device generates a predetermined number of electrical parameter values from the sensed waveforms.

4.3.1 Active Power

Active power is proportional to average power as long as I and U remain constant. A way of measuring it is thus to rectify the instantaneous power $p(t)$. The already cited [239] does this, using a 4 quad analog multiplier (IC) and a rectifying circuit.

The Ferraris wheel automatically gives the active power, because the inertia of the wheel acts as an averager.

4.3.2 Instantaneous Power

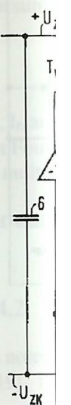
Sampling the current and the voltage with a small time difference gives rise to an error when multiplying. This error can be reduced by using a particular sampling scheme: Reversing the order of sampling regularly (every full or a multiple period) [249]. Averaging the current samples before and after any specific voltage sample (or vice-versa) improve the accuracy of timing current-voltage couples [245]. See ch. 4.2.5.3 above.

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4.3.3 Reactive Power

Remembering that the reactive power, Q , is the quadrature of active power, we see that it can be measured in the same way, employing the factor $\sin\alpha$ instead of $\cos\alpha$. Adding a 90° phase shift of α gives the quadrature:

$$P = UI \cos \alpha \quad (63)$$

$$Q = UI \sin \alpha = UI \cos (\alpha - 90^\circ) \quad (64)$$

See Figure 202 [250].

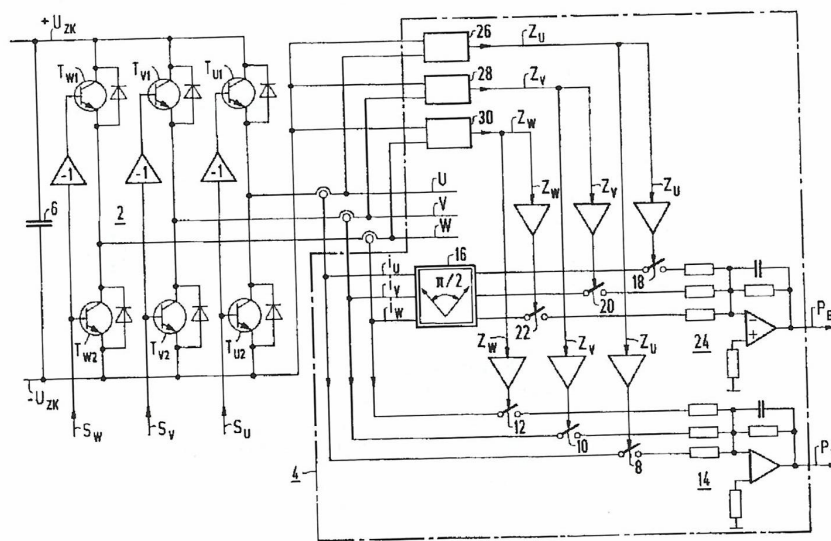


Figure 202 [250]
Circuit for Measuring of the Real and/or Reactive Power at a Converter with Impressed Direct Voltage

The invention relates to a device (4) for measuring real and/or reactive power (P_W , P_B) at one phase (U , V , W) of an inverter (2), a measurement signal (i_U , i_V , i_W) corresponding to the phase current being connected, directly for detecting the real power (P_W) or after phase rotation by $\pi/2$ for detecting the reactive power (P_B), to a switch (8, 10, 12 respectively, 18, 20, 22) which can be operated by means of a control signal, the real or reactive power (P_W and P_B , respectively) corresponding to a smoothed output signal of a ripple section (14 and 24, respectively). According to the invention, the actual switching state (Z_U , Z_V , Z_W) of the converter valve (TU_1 to TW_2), operating on this phase (U , V , W), of the inverter (2) is provided as control signal, these switching state signals (Z_U , Z_V , Z_W) in each case being determined by means of a detection device (26, 28, 30). This provides a device (4) for detecting real and/or reactive power, in which measurement errors due to dead times and/or switching times are avoided.

4.3.4 Power Factor

Power factor = active power/apparent power = $P/S = \cos \alpha$ (if u and i are sinusoidal)

In the sine case we can thus measure via the phase: (Fig. 203) [251].

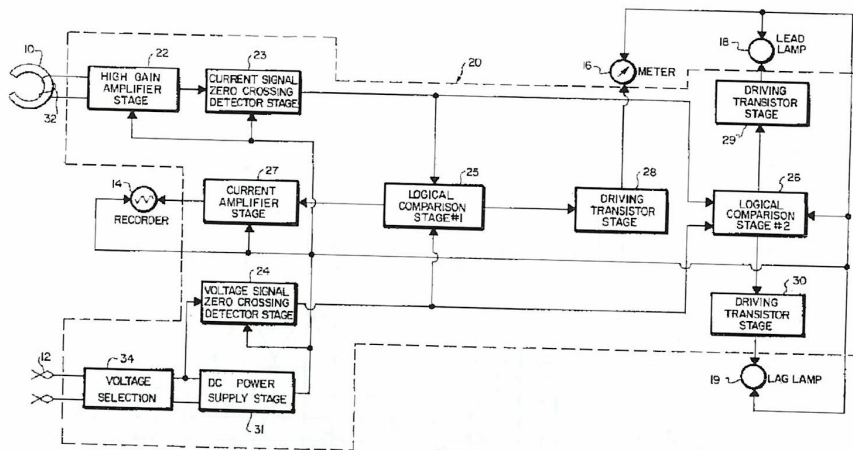


Figure 203 [251]
Power Factor Metering Device

A power factor metering device. The power factor metering device includes a novel electronic circuit for deriving the power factor from a detected voltage and current. The device includes a current clamp that may be clamped onto any conductor of a three-phase or single-phase circuit. Voltage clips are used to detect the circuit's voltage. The current clamp induces a voltage that lags the detected current by 90 electrical degrees. An amplifier stage is coupled to the induced voltage through a low input variable resistance so that the input voltage to the amplifier stage may be adjusted to correct for errors induced in the phase relationship between the detected voltage and current. The output from the amplifier stage is input into a zero crossing detector stage that changes its output state each time the output of the amplifier stage passes through zero. The output of the zero crossing detector stage is applied to one side of a pair of EXCLUSIVE-OR gates, and is also applied to one of the inputs of a bistable multivibrator. The voltage detected by the voltage clips is stepped down by a transformer and is input to a second zero crossing detector stage. The output from the second zero crossing detector stage provides the other input to the EXCLUSIVE-OR gates and the bistable multivibrator. The output of each EXCLUSIVE-OR gate is directly proportional to the phase angle between the detected voltage and current. The outputs from the two EXCLUSIVE-OR gates are amplified and are used to drive a continuous recording device and an instantaneous meter which each display the magnitude of the power factor derived from the detected current and voltage. The output from the bistable multivibrator is used to determine whether the current signal leads or lags the voltage signal.

If we have stored values of P , U and I in a memory, we can use software to calculate the power factor, $P/U \cdot I$ as in [245].

The more complicated case with distorted wave forms is treated below.

4.3.5 Average Power

Low pass filtering is simple way of averaging, see Figure 147 [198] above.

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4.4 SPECIAL APPLICATIONS

4.4.1 Power of Distorted Signals

Many power measurements are made supposing simple sinusoidal wave forms. When much harmonics are present, as in systems subject to switching, the simplified phasor formulae cannot be used. Fast digital sampling meters based on multiplying i_j and u_i samples give a correct result for the real power at frequencies under the double Nyquist limit. Note that the power frequency is twice the current frequency (Fig. 144).

Determination of active and reactive components can be done by using the Fourier- developments of the measured current and voltage wave forms; For each frequency the standard formulas are applied. The sum over all frequency then gives the total result i.e.:

$$P_{av} = V_{dc} I_{dc} + \sum V_n I_n \cos \alpha_n \quad (75)$$

$$Q_{av} = \sum V_n I_n \sin \alpha_n + \dots \quad (76)$$

V_n , I_n are RMS values. α_n is the phase shift. The measuring principle is thus to sample u , i , and to use fast Fourier Transforms (FFT) to find the magnitude and phase for each frequency. P_{av} is then found by multiplying and adding samples [253] and [254].

Corrections for not sampling i_j and u_i exactly simultaneously must be made as mentioned above.

4.4.2 DC Power and HV Power

As noted above, the Ferraris wheel meter can be used after an AC-DC conversion by e.g. transducers [219]. The use of transducers is shown in Figure 204 [255].

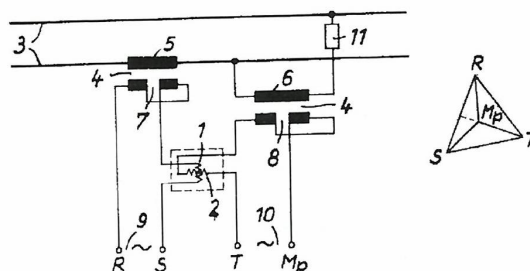


Figure 204 [255]
Transducer Measuring Arrangement

The principles for measuring on HV-lines are the same as for low voltage. What differs is the choice of sensors, see Chapters 1 and 2. Current transformers, Hall devices or Faraday cells are popular current sensors and capacitive transducers or Pockels cells are popular voltage sensors.

Low voltage transducers are being used for high voltage measurements after that the voltage has been divided down to a suitable level. Capacitive voltage dividers are popular, but both resistive and inductive ones can be used.



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Digital addition of each phase's power is shown in Figure 206 [257]. The traditional Two- Watt meter method for 3 phase power measuring is not being treated here.

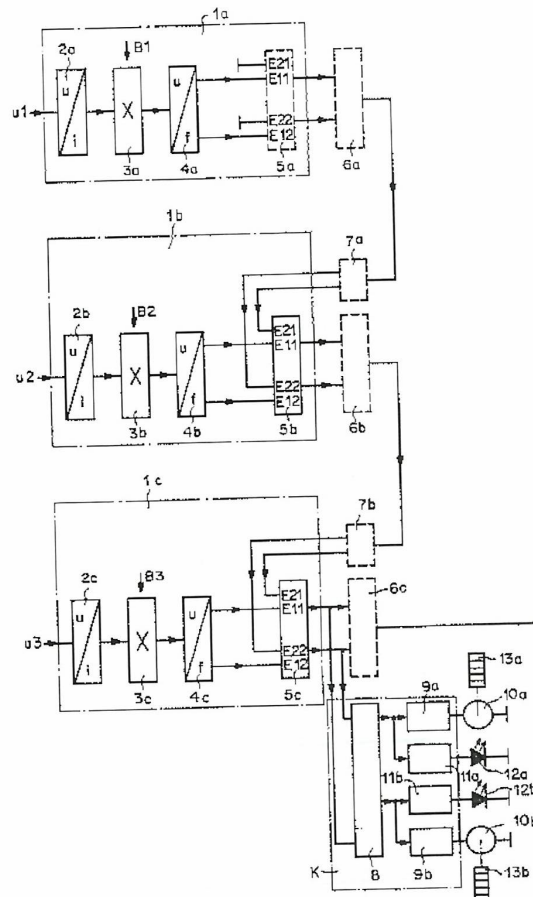


Figure 206 [257]
Three Phase Summing Energy Meter

Each input circuit (1a-1c) comprises a cascade connection of a voltage-to-current converter (2), multiplier (3), voltage-to-frequency converter (4) and adder (5). Output from each of the first two adders (5a, 5b) is forwarded via a ternary encoder (6a, 6b) and decoder (7a, 7b) to the adder of the succeeding input circuit. The sum from the final adder (5c) is encoded (6c) for transmission and is also fed to a reversible counter (8) supplying the drivers (9a, 9b) of stepper motors (10a, 10b) for mechanical indicators (13a, 13b). The integrated counter and driver (K) includes also driving circuits (11a, 11b) for LEDs (12a, 12b) which flash in synchronism with the outputs of the counter (8), one for positive and the other for negative sums.

4.4.4 High Frequency Power

We have treated the principles of measurement above in ch. 4.2. The choice of sensor is of particular interest; Bolometric Sensors, thermocouples, hot carrier or Schottky diodes are common. Calorimetry and crystals are also being used. [260].

[331] gives a good overview of detection ranges and reaction time of the various sensors.

[259] states that:

"Average microwave power up to about 10 mW is usually measured by bolometric or thermocouple sensors. The basis for bolometric power measurement is that when power is dissipated in a resistive element, a corresponding change occurs in the elements resistance. Measuring power with thin-film thermocouples is also widely used in the microwave region. These sensors have the same advantage as diodes in that only a simple dc millivolt meter is needed to display the detected voltage. Moreover, the thin-film thermocouple may be easily matched to transmission line operating as a matched load, and used as broad-band meter. However, high speed can not be achieved in such power sensors, because they depend upon the use of a rise in the lattice temperature. Further, it is necessary to make a power sensor element small compared with the operating wavelength and this causes a decrease in the sensitivity." A sensor exploiting the hot carrier effect of L-H junctions is illustrated in Figure 207 and 208 [259].

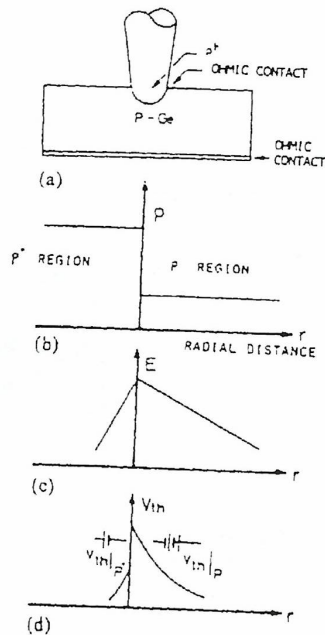


Figure 207 [259] ©1981 IEEE
 Charge Carriers Distribution, Electric Field and Thermoelectric Voltage
 due to Hot Carrier Effect of L-H Junction

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Figure 209 [2
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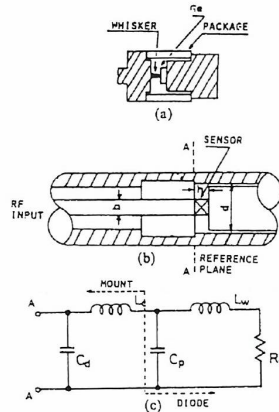
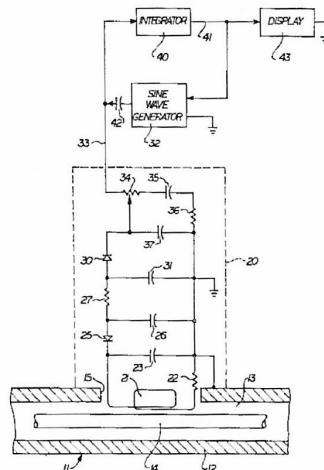


Figure 208 [259] ©1981 IEEE

Hot-carrier Power Sensor, Broad-Band Coaxial Mount and its Equivalent Circuit

Figure 209 [260] shows the use of a diode detector and a pick-up element in a coaxial transmission line.

Figure 209 [260]
RF Watt Meter

The induction loop (21) in the pick-up element is connected to a principle detector (25). A secondary detector (30) is connected in opposition to the latter (25). The detectors are close to each other and subject to the same diode thermal environment. A sine wave generator supplies a wave signal to the sec. detector in opposition to the wave signal supplied to the principal detector from the inductive loop. The d.c. portion of the resulting signal representing the difference between the opposed signals is integrated (40) and the integrated output is used as the amplitude in the generated sine wave (32). When the circuit is in balance, the integrated output matches the amplitude of the inductive wave form and can be used as an output indicating (43) measured power in the coaxial transmission cable (11).

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Figure 207

A hyper frequent power sensing circuit employing a FET (6) is illustrated in Figure 210 [326].

The FET (6) has a double function: It's gate is grounded and non-polarized, so that it act either as a capacitor or a diode, depending on whether it senses or not a current in the circuit. Additionally, the FET participates with it's equivalent capacitance to the adaption circuit.

The input is at (i).

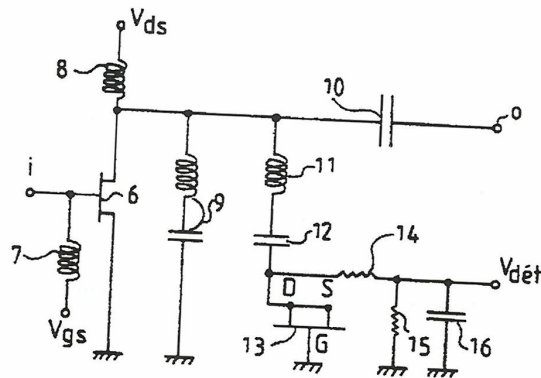


Figure 210 [326]
Hyperfrequent Power Sensing Circuit

Problems with diode detectors

Diode detectors have their particular problems, notably a temperature dependent threshold voltage. Figure 211 [292] shows a circuit that compensates for this via a biasing circuit.

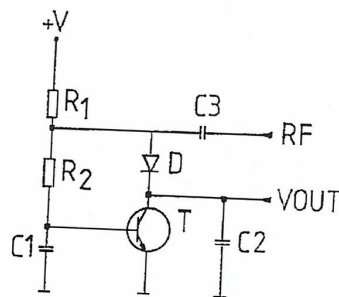


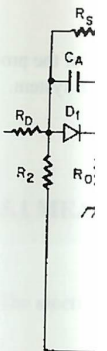
Figure 211 [292]
Biasing Circuitry for a Diode Detector

The invention relates to a biasing circuitry in a power level detector used for power control of a high-frequency power amplifier. According to the invention, to compensate for variation caused in the detector diode (D) threshold voltage by temperature changes, a constant-power source (T, R1, R2) is used by means of which the operating point of the detector diode (D) is set at a constant level and close to the angle point of the threshold voltage of the diode (D).

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The problem of limited range (see also Figure 163) has another solution in combining two diodes arranged with different shunt capacitances, so that their sensitivities are different. Figure 212 [327].

D1 and D2 are power sensing Schottky diodes formed on a single IC or individual diodes. Capacitor C_+ increases the shunt capacitance, $C_d + C_1$ of D1, so that it is 10 times that of D2. The reduction in sensitivity is 20 dB.

The total range of this arrangement is 40 dB. It is used as a radiation detector.

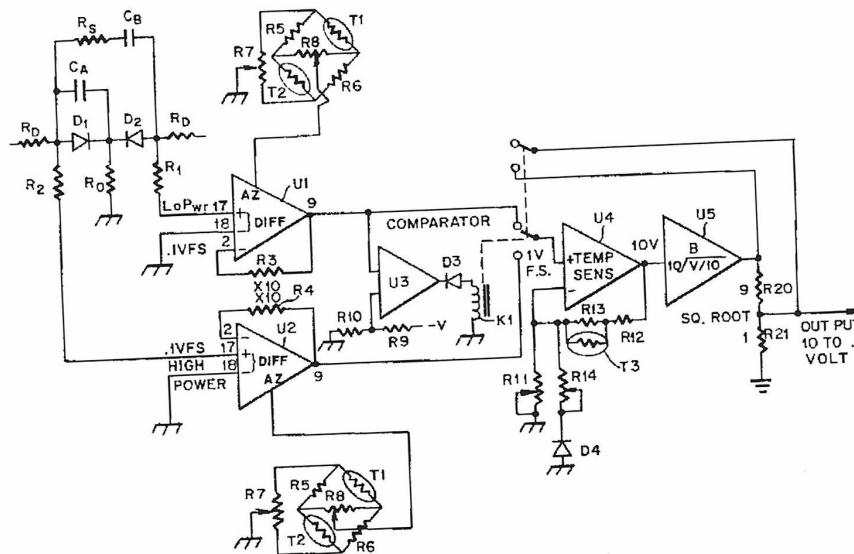


Figure 212 [327]
Wide Power Range Radiation Monitor

A wide power range radiation monitor includes a pair of diodes with their cathodes interconnected and with an additional capacitor coupled in parallel to one of the diodes. The detector of the radiation monitor provides two outputs, a low power output and a high power output, which outputs are connected to the anodes of the detector diodes. The arrangement of dual diodes and capacitance provide the diode detector of the monitor with a greater than 40 dB square law region.

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Problems with Ferraris wheel Meters

- The Ferraris wheels response curve is not linear. Extra hardware, such as permanent magnets are being used for compensation (Fig. 170 above).

Figure 173 illustrates the use of a compensating current.

- It is subject to wear.
- The measurement transformers used are nonlinear.
- It is inaccurate in measuring higher harmonics. This is of increasing concern because of the proliferation of electronic loads with unlinear characteristics, injecting harmonics into the system. In [289] Elham B. Makram et al [291] and [290] Girgis et al. determine this error.
- The information that it can deliver is very limited.
- It consumes energy: one can regard it as a small motor.

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