The Theories and Modeling of the Kilowatt-Hour Meter

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Contents

Abstract

This work presents the basic understanding of how a modern induction-type kilowatt-hour meter works as well as the physical theories that support this understanding. These physical theories include Faraday's law, Lenz's law, and ohm's law, to name a few. A mathematical model will be derived and used to find certain relationships between input variables and output variables. In order to create this model, assumptions have to be used to a certain degree.

History

Have you ever wondered what that electric meter outside your house with the little dials on it does and how it works? It isn't a machine where you can find out how it works just by looking at it. It takes a grasp of the concepts of magnetism, currents, and fundamental laws of physics to have a complete understanding. This machine is quite useful, and accurately measures electricity being used by your household. A kilowatt-hour meter is a device that mechanically multiplies the amperage and the potential difference of a current. It then records the power usage over time to find the total energy used.

The beginnings of the watt-hour meter in some ways predate the Edison's invention of the light bulb. The recording of energy consumption also has its roots in the late 1800s. In 1872 Samuel Gardiner took out the first known patent on an electric meter. This was a DC lamp-hour meter that was a clock with an electromagnet that started and stopped the mechanism. It wasn't until 1879 that Thomas Edison actually developed a practical light bulb. This DC lamp-hour meter only calculated the time that electricity was flowing and not the amount that was actually used.[1]

In 1882 Edison started up his first electric company for incandescent illumination. Initially he started out with a per-lamp rate. This was unsatisfactory so he developed a chemical ampere-hour meter that consisted of a jar holding two zinc plates connected across a shunt in the customer's circuit. Each month the electrodes were weighed and the customer's bill was determined from the change in their weight. This meter was inefficient and error-prone. Edison did also develop a motor-type meter but preferred the chemical meter because of his interest in chemistry.[1]

In 1886 Professor Forbes of London, England came up with the first meter for use on AC circuits that used a heating element connected into the circuit which operated a small windmill connected to a register. Unfortunately, this meter was far too delicate for commercial use. In 1914 WWI interrupted the supply of tungsten, a key component in the steel used in meter brake magnets, and the manufacturers switched to a different type of steel using chromium. In 1928 George Westinghouse introduced the first socket-type meter, the OB "detachable". This allowed meters to be tested easily and faulty meters to be replaced effortlessly. [1]

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[1] www.watthourmeters.com /history.html

Up to the mid-1930s, meters made by different manufacturers (or even different versions of the same model) were made with little attention to consistency in design. This resulted in a problem for electric utilities in that a meter change-out often required rearranging the wiring to the meter. In 1934, a committee consisting of representatives from the manufacturers and the larger electric utilities came up with two new standardized designs ("S" type of socket and "A-base" or bottom-connected) for the meter enclosures. This simplified meter change-outs in the field to simply taking out the old meter and installing the new.[2]

In the late 1930s a major improvement was needed in response to a problem that became obvious once meters were installed outdoors in rural areas. After lightning storms, some meters started running fast since the brake magnets were weakened by power surges during the storm. This was solved by replacing the chrome steel magnets with magnets that were made of Alnico, which did a much better job of holding their strength. Westinghouse took a different approach by heavily copper-plating their chrome steel magnets and continued this practice until 1954.[2]

In 1940 GE began development on a new type of bearing using magnets to suspend the aluminum disk and axle. Since the US was entering WWII at the time, work was put on hold until after military involvement ceased.[2]

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[2] www.watthourmeters.com /history.html

Physical Model: Description

A modern single-phase, induction-type kilowatt-hour meter consists of a base with contacts on the back side that allow for quick disconnection for service and replacement. Each kind of meter has a different contact pattern called a socket type. The one we will be describing has four contacts on the backside of the meter with the arrangement as shown in figure 1.

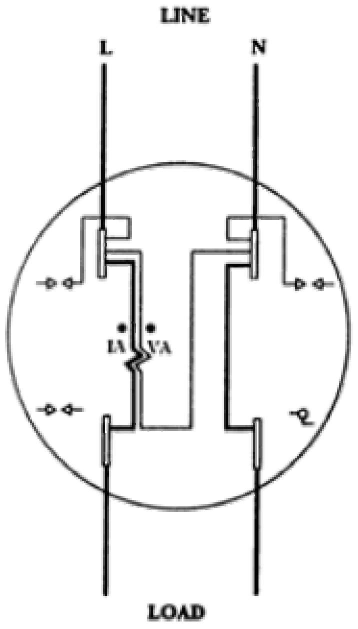

Figure 1

When a meter is removed, the base or socket that the meter connects to is still connected into the power lines. The figure above shows the four main wires that would still be connected to the base as well as the four contacts that accept the contact blades of the meter. The remaining electrical schematic is just a summary of what is going on in a watt-hour meter. The meter itself is enclosed in a glass or plastic cover so as to prevent corrosion and tampering (as shown in figure 2). Inside, there is a mechanical counting system that counts the revolutions of an aluminum disk and in turn (no pun intended), displays the kilowatts of energy used. The ratio of

Figure 2

kilowatts displayed to the turns of the disk is called the disk constant, $K_{h.}$[3] The customer then is billed by the electric company according to how many kilowatts are used (approximately 5 to 10 cents per kilowatt).[4] The aluminum disk in the meter is acted upon by three coils; one coil creates magnetic flux that is proportional to the voltage and the other two produce a magnetic flux that is proportional to the current. As the disk moves through the magnetic field of the first coil, the flux through the disk changes, causing an emf around paths through the disk. This occurs due to Faraday's law, which shows that the change in flux over time equals the electric field in a conductor.[5] Since the disk is conducting, this emf will cause current to flow due to Ohm's law.[6] This current will be directly proportional to the emf and indirectly proportional to the resistance of the aluminum disk. The current will circulate in a direction to produce a magnetic field opposite to the uniform field. This direction is determined by Lenz's law where "The direction of any magnetic induction effect is such as to oppose the cause of the effect."[7] It is helpful to use the right-hand rule for a closed loop to determine the direction of the current flow to produce this opposing field.[7] The circulating current then interacts with the B-field of the two coils that induce fluxes that are proportional to the current. These two coils are usually located under the aluminum disk while the voltage coil is usually located on top of the aluminum disk. The circulating current that interacts with the B-field from the lower coils produces a force that creates a counter-clockwise torque on the aluminum disk. At first inspection you would suspect that the aluminum disk would constantly accelerate and calculate some erroneous energy reading. This is not true. The torque is opposed by a force that is created by a "c" shaped permanent magnet. This permanent magnet is oriented with the aluminum disk as shown in figure 3. This permanent magnet interacts with eddy currents that are produced by the change of flux. This change of flux is created because the magnet is moving in relation to the aluminum disk. The same affect is created when you drop a bar magnet down a copper tube. A force opposes gravity that slows down the magnet. The force is proportional to the speed

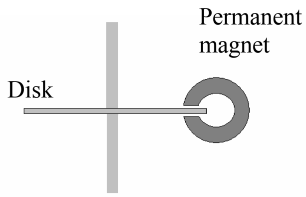

Figure 3

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[3] Measurement of Alternating-Current Energy, pp. 83

[4] Ames Electric Services

[5] Sears and Zemansky's *University Physics*, pp. 958.

[6] Sears and Zemansky's *University Physics*, pp. 814.

[7] Handbook for Electrical Metermen, pp. 20.

of the bar magnet just as the force created by the “c” shaped magnet is proportional to the speed of the rotating disk. The rotating disk is mounted on an axle that has a magnetic thrust bearing at the bottom and a small needle at the top. This minimizes the friction and also minimizes the error of the meter at small current loads.

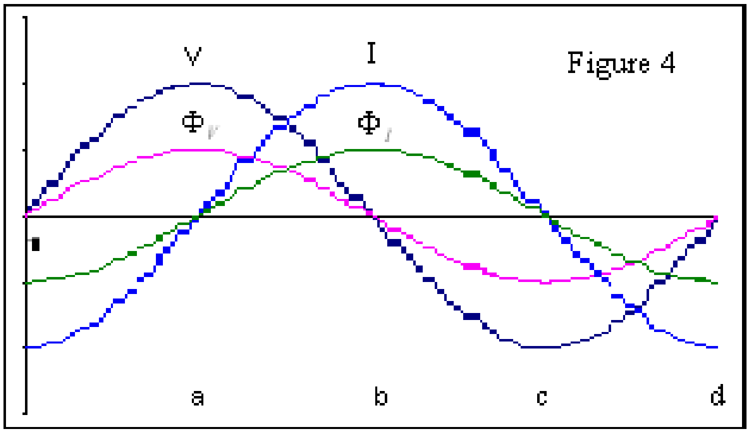
Figure 4

Since this kilowatt-hour meter is an AC model it has to be noted that the voltage and current varies sinusoidally with time. One might think that the disk would just oscillate and wouldn’t turn at all. Since both the voltage and current vary with time, the direction of torque does not change and the disk continues to move in the same direction. In figure 4 the sinusoidal functions of current (I) and potential difference (V) are shown. Their corresponding fluxes (Φ_V and Φ_I) are also shown and should be noted that they are proportional as well. The graph is divided in to time instants a, b, c, and d. During time instant “a” the voltage is at its maximum and so is the corresponding flux. Since the flux is not changing in the upper coil, no current is induced in the disk. At this same instant the current is at zero and so is the flux due to the current. At time instant “b” the voltage is rapidly decreasing and so is the flux due to the voltage. Using Faraday’s law, $\frac{d\Phi}{dt} = -emf$, we find that the emf or voltage in the aluminum disk is at a maximum and creates a maximum current. This current moves through the area of highest magnetic field density created by both current coils below the aluminum disk. As you can see at time instant “b” both the current and the flux created by the current are at their highest. This is a time where the torque is at its highest for a given current and voltage. At time instant “c” the voltage is at a minimum and the “voltage flux” is as well. Since the flux is not changing, no current is induced in the aluminum disk and it is irrelevant whether the current is even present. At any instance between the previous time instants described there is torque created in a counter clockwise direction. The torque between the described time instants is not as great as the torque at "b" and "d". At time instant "d" the flux due to the voltage is rapidly increasing which creates a negative emf. This negative potential difference causes the current in the aluminum disk to follow a path that is opposite that of time instant "b". As you notice though, the current at "d" is negative and still creates a torque in the same direction. This torque causes the meter to turn and, over time causes the mechanical counting system to log the kilowatts of energy used. Table 1 shows how the polarity and condition of the fluxes contribute to the rotation of the disk.

Table 1 (Information gathered from Handbook for Electrical Metermen, pp. 42)		TIME INSTANT			
		A	B	C	D
Polarity of Flux	Φ_I	0	+	0	-
Polarity of Flux	Φ_V	+	0	-	0
Condition of Flux	Φ_I	Increasing	Maximum	Decreasing	Minimum
Condition of Flux	Φ_V	Maximum	Decreasing	Minimum	Increasing
emf Polarity		0	+	0	-
emf Condition		Increasing	Maximum	Decreasing	Minimum
Rotation of Disk		Counter Clockwise	Counter Clockwise	Counter Clockwise	Counter Clockwise

To solve problems in alternative kilowatt-hour designs and calculate various outputs after changing the input variables, a model needs to be developed and implemented. This can allow known quantities to remain constant while changing the remaining variables to arrive with the desired output. Before we begin explaining the model and concepts involved with developing the model, we need to lay down some basic assumptions that will allow us to make the model without extensive calculations. Though this reduces the accuracy of the relationships found, it would be nearly impossible to mathematically model otherwise.

The type of kilowatt-meter that we will model is an **induction-type** that can only measure single phase AC current. The model is universal with respect to the various manufacturers (Westinghouse, Duncan, Shallenberger, Sangamo). We will assume that

the current source and load contribute to a **perfect sinusoidal waveform**. Waveforms that are not ideal can affect the accuracy of any induction-type watt-hour meter. [1]
The meter is assumed to **operate only within its specified range** (voltage and amperage). In induction type meters accuracy is the least at extremely light and over-specified loads. At extremely light loads the ratio of coil-induced torque to friction induced torque is at a minimum and the percentage of error is at its highest. [1] The **drag** produced by the counting mechanism and the axle mounts of the aluminum disk are negligible. The effects of **varying conductivity** of the aluminum disk due to temperature change cancel each other out. That is, if the temperature of the outside environment increases, the conductivity decreases. When the conductivity decreases, the torque produced by the coils will decrease. The torque produced by the dampening permanent magnet shall also decrease so that the net torque is approximately the same for given current characteristics. In our model the approximate difference is negligible. These assumptions will allow us to make some generalizations that will make our mathematical model possible.

Mathematical Model

Meters are subject to a wide range of temperatures. A mathematical model of the meter will help to determine whether or not a significant change in temperature will affect the accuracy of the meter. Once we arrive at a mathematical model, we will use a computer program to approximate the disk constant of the meter being tested. This disk constant will relate the number of turns of the disk to the amount of energy being used. To begin to model the meter mathematically it is helpful to start with the Biot and Savart Law. This will allow us to calculate the magnetic flux and the current in the aluminum disk.

$$B_V = \frac{\mu_0 N I r_{vc}^{\,2}}{2\left(x^2 + r_{vc}^{\,2}\right)^{3/2}}$$ (B-field on the disk caused by a coil with N circular loops) (eq. 1)

where,

$\mu_0 = 4\pi \times 10^{-7} T \cdot m / A$

N = number of circular loops

I = current through coil

r_{vc} = radius of the coil

x = distance from coil to disk

The equation, $I = \frac{V}{R_{Coil}}$ can replace "I" in equation 1 to give

$$B_V = \frac{\mu_0 N \left(\frac{V}{R_{Coil}}\right) r_{vc}^{\,2}}{2\left(x^2 + r_{vc}^{\,2}\right)^{3/2}}$$ (eq. 2)

where,

V = potential difference between the contacts on the meter

R_{Coil} = resistance of the coil

The total magnetic flux through the disk is the sum of the contributions from the individual area elements, caused by a potential difference in the AC circuit:

$$\Phi_V = \iint B_V \cdot dA = \iint B_V \cos\phi \, dA$$ (the magnetic flux through the aluminum disk) (eq. 3)

where,

f = Angle between the area vector and the B-field vector

dA = Magnitude of the area vector

After substituting eq. 2 into eq. 3, and since $f = 0°$ and $\sin f = 1$, we get

$$\Phi_V = \iint \frac{\text{m}_0 N \left(\frac{V}{R_{Coil}}\right) r_{vc}^{\ 2}}{2\left(x^2 + r_{vc}^{\ 2}\right)^{3/2}} dA \qquad \text{(eq. 4)}$$

We can then use Faraday's law of induction to find the potential in the aluminum disk created by the voltage coil.

$$\frac{d\Phi}{dt} = -emf \quad \text{(Faraday's law of induction)} \qquad \text{(eq. 5)}$$

Using Lenz's law and the right hand rule, the orientation of the emf of the eddy currents on the disk can be determined. Since we are not determining the emf of the eddy currents vectorially the negative sign in the equation can be omitted.

Then, by substituting equation 4 into equation 5 we find,

$$\frac{d}{dt}\iint \frac{\text{m}_0 N \left(\frac{V}{R_{Coil}}\right) r_{vc}^{\ 2}}{2\left(x^2 + r_{vc}^{\ 2}\right)^{3/2}} dA = emf \qquad \text{(eq. 6)}$$

In the aluminum disk eddy currents are always flowing in circular loops as shown in figure 5. Since there is always an eddy current moving under the voltage coil as another is moving from out of under the coil, we can assume that there is constantly an eddy current under the coil. This current contributes to the force and, consequently, to the torque applied to the rotating mass.

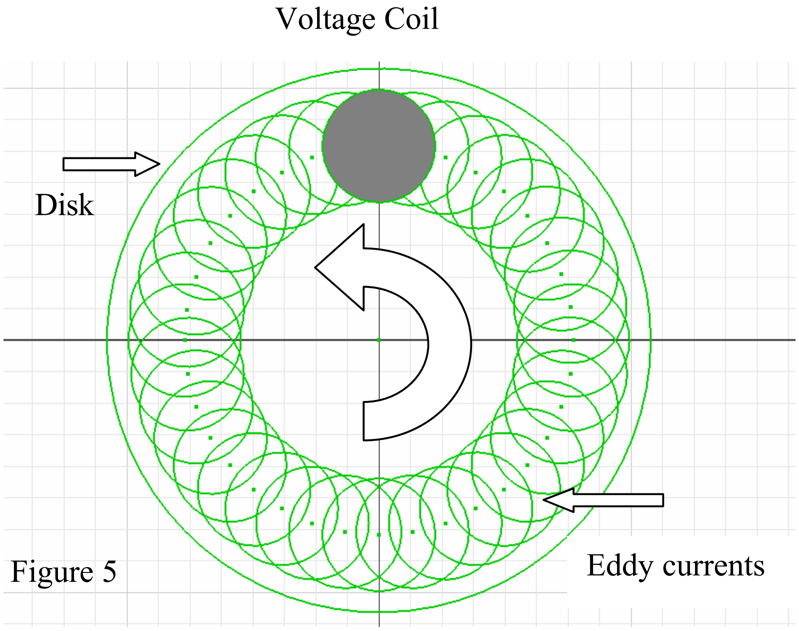

Figure 5

Since it is too difficult to calculate the current in a disk with random eddy currents, we will model the area directly under the voltage coil using an aluminum washer. Using this method will allow us to find the current in the disk in a concentrated area.

We can use Ohm's Law to substitute IR for emf

$$V = I_{Disk} R_{Disk} = emf \qquad \text{(eq. 7)}$$

in equation 6, where I is the current in the disk and R is the resistance in the disk The result follows.

$$\frac{d}{dt}\iint \frac{\mu_0 N\left(\frac{V}{R_{Coil}}\right) r_{vc}^{\,2}}{2\left(x^2 + r_{vc}^{\,2}\right)^{3/2}}\, dA = I_{Disk} R_{Disk} \qquad \text{(eq. 8)}$$

Rearranging equation 8 to solve for the current in the disk we get:

$$\frac{1}{R_{Disk}}\frac{d}{dt}\iint \frac{\mu_0 N\left(\frac{V}{R_{Coil}}\right) r_{vc}^{\,2}}{2\left(x^2 + r_{vc}^{\,2}\right)^{3/2}}\, dA = I_{Disk} \qquad \text{(eq. 9)}$$

where R_{Disk} is the resistance in a washer shaped disk.

Since there are two coils,

$$2\left(\vec{I}\times\vec{B}\right)=\vec{F} \qquad \text{(eq. 10)}$$

where F is the force produced.

However, dealing with only magnitudes, equation 10 can be rewritten as:

$$2\left(IB\sin \mathrm{q}\right)=F \qquad \text{(eq. 11)}$$

where q = the angle between the I and B vectors. However, since I and B will always be perpendicular in this case, q = 90° and sin q = 1. So equation 11 simplifies to the following:

$$2IB=F \qquad \text{(eq. 12)}$$

If we substitute equation 9 into equation 12 for current, we have the resulting equation.

$$2B\frac{1}{R_{Disk}}\frac{d}{dt}\iint\frac{\mathrm{m}_0 N\left(\frac{V}{R_{Coil}}\right)r_{vc}^{\,2}}{2\left(x^2+r_{vc}^{\,2}\right)^{3/2}}dA=F \qquad \text{(eq. 13)}$$

To find the torque, this equation can be used.

$$\overrightarrow{r_{disk}}\times\vec{F}=\vec{\mathrm{t}} \qquad \text{(eq. 14)}$$

Again, only magnitudes can be used, and the equation looks like the following:

$$r_{disk}F\sin \mathrm{a}=\mathrm{t} \qquad \text{(eq. 15)}$$

where α is the angle between the r and F vectors. However, in the case at hand, the vectors will again be perpendicular at all times, so α=90°, sin α = 1, and the equation simplifies to

$$r_{disk}F=\mathrm{t} \qquad \text{(eq. 16)}$$

If we substitute equation 13 in for force, the new equation for torque is as follows.

$$2Br_{disk}\frac{1}{R_{Disk}}\frac{d}{dt}\iint\frac{\mathrm{m}_0 N\left(\frac{V}{R_{Coil}}\right)r_{vc}^{\,2}}{2\left(x^2+r_{vc}^{\,2}\right)^{3/2}}dA=\mathrm{t} \qquad \text{(eq. 17)}$$

We know that

$$\mathrm{t}\propto P \qquad \text{(eq. 18)}$$

where P is power. If the aluminum disk in any induction-type kilowatt-hour meter had a needle fixed on the disk and graduations marked out on the fixed meter, this combination would produce a very accurate Watt meter (42, Handbook for Electrical Metermen). Knowing the above proportion, we can do some arithmetic.

$$E = \int P\,dt \qquad \text{(eq. 19)}$$

where E is the energy used by the customer.

Using equation 18, the following relation can be expressed.

$$\int \mathrm{t}\ dt \propto \int P\,dt \qquad \text{(eq. 20)}$$

Substituting equation 19 in to equation 20, we obtain

$$\int \mathrm{t}\ dt \propto E \qquad \text{(eq. 21)}$$

$$k\int \mathrm{t}\ dt = Energy \qquad \text{(eq. 22)}$$

where k is a measurement constant. This value is the amount of energy used by the customer. Then by substituting equation 17 into equation 22, we get a result of

$$Energy = k\int 2Br_{disk}\,\frac{1}{R_{Disk}}\,\frac{d}{dt}\iint \frac{N\left(\frac{V}{R_{Coil}}\right)r_{vc}^{\ 2}}{\left(x^2 + r_{vc}^{\ 2}\right)^{3/2}}\,dAdt \qquad \text{(eq. 23)}$$

We then use Biot and Savart's Law for the B-field of the two current coils,

$$B_{CC} = \frac{\mathrm{m}_0 N_{cc} I r_{cc}^{\ 2}}{2\left(x_{cc}^{\ 2} + r_{cc}^{\ 2}\right)^{3/2}}$$

in equation 23. Where

N_{cc} = number of turns in the current coil
r_{cc} = radius of the current coil
x_{cc} = distance from the current coil to the disk

After dividing by 2/2 we get

$$Energy = k\int \frac{\mathrm{m}_0 N_{cc} I r_{cc}^{\ 2}}{\left(x_{cc}^{\ 2} + r_{cc}^{\ 2}\right)^{3/2}}\,r_{disk}\,\frac{1}{R_{Disk}}\,\frac{d}{dt}\iint \frac{N\left(\frac{V}{R_{Coil}}\right)r_{vc}^{\ 2}}{\left(x^2 + r_{vc}^{\ 2}\right)^{3/2}}\,dAdt \qquad \text{(eq. 24)}$$

From our final equation we find that the energy is directly proportional to the voltage and current from the load. This is expected since energy is the current multiplied by potential difference, all integrated with respect to time. It is also found that the energy is indirectly related to both the resistance of the disk and the resistance of the coil. And since the temperature coefficients of resistivity of aluminum (the disk) and copper (the coils) are nearly the same (3.9 x 10^{-3} and 3.93 x 10^{-3}, respectively) any change of temperature is insignificant. As the temperature increases, the resistivity of the aluminum disk also increases, but so does the resistivity of the coil by approximately the same amount. As temperature increases, the radius of the disk will also increase, but since the radius from the axis of the disk to the point of force never changes, it does not matter how large the overall radius gets. As a result of these observations, we find that any change in temperature is negligible.

Now that we have drawn out a mathematical model, we will use a computer program to approximate the disk constant of the meter being tested. Before using the program, the meter needs to be subjected to a known load by a trained professional. The data collected from the test and the characteristics of the meter then need to be entered into the program to find the disk constant, k. K multiplied by the number of disk turns gives the amount of energy, measured in kilowatts. The disk constant is important to know when recalibrating an outdated meter. The program can be found in Appendix II and the data from a sample run can be found in Appendix III.

Future Development

Modern technology has allowed us to measure energy usage by a seemingly simpler device that is easier to mathematically model. The induction-type energy meter is still the most widely used; however some digital models are entering the market. The digital meters determine power by directly multiplying the current by the potential difference and record this result over time to obtain a value for energy used.

There are a few advantages of using a digital meter over an analog meter. The primary reason is the fact that digital meters do not have moving parts. This reduces the error do to mechanical parts wearing out after time. Also a digital meter is more accurate; most digital meters have an error of 0.8%.[8] While the error of a standard, analog meter is at most 2%.[9]

Some digital meters are designed using large-scale integration circuits (LSI).[10] LSIs contain anywhere from 500 to 1000 circuit elements.[11] An LSI uses a digital voltmeter and an ammeter to measure the instantaneous potential difference and current. Then it is capable of converting the values into computer code. After that, it performs the necessary multiplication to obtain the wattage used and records the amount in static memory.[5]

Another advance in the modern meter is the ability to transmit the current readings to a remote observer. With this capability, the power company can effectively monitor all the meters from a central location instead of physically looking at each meter individually.

Even though the newer, digital meters are more reliable they are still not widely used. Although the benefits of a digital meter don't warrant an immediate replacement of all analog meters, when analog meters wear out, digital versions are installed in their place.[12]

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[8] http://www.analog.com/library/whitepapers/dataConverters/pdf/energymeterua_42000.pdf

[9] Handbook for Electrical Metermen, pp. 49

[10] http://www.apctt.org/database/to7009.html

[11] http://www.computerhope.com/jargon/l/largscal.htm

[12] http://www.analog.com/library/whitepapers/dataConverters/pdf/energymeterua_42000.pdf

Appendix I: GLOSSARY

PARTS OF AN ELECTRICITY METER

<u>BASE</u> – *S-Base, A-Base, K-Base, P-Base, Switchboard*

The base is the platform on which all of the other meter parts are mounted. The connections from the service to the electricity meter are made through the base. There are several different base configurations.

S-Base – The *S-Base* or "socket base" is the most common. It is round and plugs into a *Socket* or *Mounting Device*. Meters of all kinds both single phase or polyphase and Self-Contained or transformer-rated are made in this configuration. These meter designs can have voltages up to 600 volts and currents up to 300 amperes.

A-Base – The *A-Base* or "bottom connected" meter mounts to the surface of a wall or box and is wired directly into the service via a connection block on the bottom of the housing and usually a *Safety Test Switch*. Meters of all kinds both single phase or polyphase and Self-Contained or transformer-rated are made in this configuration. These meter designs can have voltages up to 480 volts and currents up to 100 amperes.

K-Base – The *K-Base* meter is known as an extended range meter. It is a bolt in construction with large buss bars, mounted in very large mounting devices sometimes called "coffins". These meters have built-in CTs and can meter currents up to 600 amperes and voltages up to 480 volts.

P-Base – The *P-Base* meter is like an A-Base meter except that in place of the connection block into which wires are inserted and tightened, the P-Base has current conductors protruding out of its bottom block. There is a mounting device to which the service is wired and into which the current conductors of the P-Base meter are clamped. It is a more easily removable bottom connected meter. Few utilities use this design. Polyphase Self-Contained and transformer-rated meters are made in this configuration. These meter designs can have voltages up to 480 volts and currents up to 100 amperes.

<u>FRAME</u> – The metal casting that holds the voltage and current elements, disk and register in a physical relationship and is mounted to the base plate. This term applies to *Induction* or "disk" type meters. Solid state meters have card cages or chassis in place of the frame.

<u>REGISTER</u> – The *Register* is the device that records the amount of energy measured by the electricity meter. There are many different types of registers. On induction meters, registers are driven by a gear that is coupled to the meter disk. Registers may be of the 4 or 5 dial type, where the device can read 9999 or 99999 kilo-watt hours. They may be a *Pointer* type were a pointer indicates the number, or of the

Cyclometer type which shows a single number for each place through a window in the register face. An electricity meter may have either a dial or Cyclometer register.

ELEMENT or STATOR – The meter may have1, 2, 2 ½, or 3 elements. In an induction meter, an element is made up of a voltage coil and a current coil. In a single phase meter, there is 1 element; in a polyphase meter there may be 2, 2 ½, or 3 elements. A ½ element is one current coil usually located in the B phase (rear) that is shared by A and/or C element current coil. There is no B voltage coil and the meter measures the B phase power based on the assumption that the voltages are equal in all phases. This type of meter is sometimes called a "compromise" meter. The elements of a meter produce a driving force on the disk that is proportional to the energy measured by the element. The elements of a polyphase meter are referred to as A-phase, B-phase or C-phase element; Left, Center (Rear) or Right element; or Upper, Middle or Lower element. All of these refer to the element of the left side of the frame facing the meter, the rear of the frame and the right of the frame. (i.e. A-phase, Left and Upper all refer to the element on the left side of the frame facing the meter.) The solid state meter also has elements but they are referred to as "voltage and current sensors". It is common for the "voltage sensors" to be resistive dividers and the "current sensors" to be small CTs or embedded coils in a straight conductor. These sensors provide small AC signals to the electronic measuring circuits of the meter that are proportional to the voltage and current wave forms they are sensing. The measuring circuits can determine the voltage and current magnitudes and the phase shift between them (power factor). The microprocessor can scale the values to calculate the watthours, varhours, Qhours, etc., being metered.

DISK – The *Disk* is the part of the induction meter that turns. It is positioned in a gap between the voltage coil and current coil of the element and is acted on by the magnetic flux generated by the element that is proportional to the energy being measured. This magnetic flux causes the disk to rotate in a counter clockwise (CCW) direction looking down on the top of the meter if all the polarities of the connections are correct. Solid state meters do not have disks.

DRAG (DAMPENING) MAGNETS – The *Drag Magnet* is usually a pair of permanent magnets mounted one on each side of the meter disk. These magnets provide a "drag" or retarding force on the disk that becomes larger as the disk speeds up. The strength of these magnets determines the *Full Load* calibration of the meter. Solid state meters do not have drag magnets.

FULL LOAD ADJUSTMENT – The *Full Load Adjustment* on an induction meter is usually a screw type shunt mounted between the pole faces of one of the drag magnets. Depending on how far it is inserted into the magnet determines how much of the magnetic flux is shunted from going through the disk to the other magnet. This controls the strength of the magnet and thus the retarding force produced by the drag magnets. This adjustment is made at the TA (test amperes) value. Solid state meters are calibrated by selecting resistance values or by software corrections.

LIGHT LOAD or FRICTION ADJUSTMENT – The *Light Load Adjustment* on an induction meter, sometimes referred to as the "friction adjustment," corrects the unbalance in flux between the left and right pole face of the element. This removes a condition referred to as *Creep*, a condition where the disk turns when only voltage and no current are flowing through the meter. It also adjusts the calibration of the meter at 10% of the TA value. Solid state meters are calibrated by selecting resistance values or by software corrections.

POWER FACTOR or LAG ADJUSTMENT – The *Power Factor Adjustment* on an induction meter, sometimes referred to as the "lag adjustment," determines the phase displacement between the voltage and current flux in the meter element. This adjustment is made in a watthour meter when the current lags the voltage wave form by $60°$. Newer single phase induction meters provide no power factor adjustment. Polyphase induction meters provide a power factor adjustment for each element. Solid state meters are calibrated by selecting resistance values or by software corrections.

VOLTAGE TEST LINK or POTENTIAL CLIP – The *Voltage Test Link*, sometimes referred to as the "potential clip," is only present on Self-Contained type meters. They are slide links on the base plates of S-Base and K-Base meters; or connection blocks of A-Base and P-Base meters that are wired in series with the voltage coil leads. Opening this test link provides for isolating the voltage coil of the meter from the service for testing purposes. Tests made with this link open are known as *Open-Link Tests* and with it closed as *Closed-Link Tests*.

LIGHTING ARRESTOR – A *lighting Arrestor* is a spark gap device provided on each voltage phase of the electricity meter to shunt lighting bolts to earth ground to prevent damage to the electricity meter. They are connected to the *Line Side* of the meter.

COVER or METER GLASS – The *Cover* sometimes referred to as the "meter glass" is a protective cover placed over the frame and its parts and attached to the base plate. Covers can be made from glass, plastic or metal.

TERMS DEFINING METERS

FORM NUMBER – The *Form Number* of a meter defines how the meter is wired inside and what type of service (single phase, delta or wye) it can be used for. Form numbers are established by the ANSI – C12 Code for Electricity Metering. Many metering people do not use the form numbers when referring to the type meter. Instead, the will define it by the type of service it is used for. For example, they may refer to a form 9 meter as a "3-phase, 4-wire, wye". The problem is that forms 6, 7, 10, 14 and 16 are also "3-phase, 4-wire, wye" and they are wired differently from the form 9. The form number is printed on the name plate of the meter.

K_H, K_E, K_P – The K_H, K_E, or K_P of a meter is the measurement constant. In an induction meter the K_H is known as the "disk constant" and is the number of watthours measured by the meter of reach revolution of the disk. K_E is the same value for an electronic meter and is the number of watthours measured by the meter for each sampling period, which in reality is the time it would take for an induction meter of the same form to make one revolution. K_P is a similar value but is the watthour weight of each pulse from a pulsing type meter. If the meter measured varhours, it would of course be the varhour constant etc. These values are used by test equipment to calculate the meter accuracy by counting revolutions or pulses to determine what the meter is measuring. The measurement constant is printed on the name plate of the meter.

TA or TEST AMPERES – The *TA* is the value of current at which the meter should be calibrated. This is known as the *Full Load* test current. The TA is printed on the name plate of the meter.

CLASS – The *Class* of a meter is its maximum current operation point. For example, a residential meter is a class 200. This means that the meter is within its stated accuracy up to 200 amperes. The Class of the meter is printed on the name plate of the meter.

WATTHOUR – A *Watthour* meter measures the active power flowing through it according to the relationship $ActivePower = Voltage \times Current \times Cos\Theta$ (Phase angle between voltage and current). Watthour meters are available in all forms and base styles; in induction or electronic and in Self-Contained or transformer-rated types. In a unity power factor (1.0 P.F.) watthour test, the voltage and current are in phase with $0°$ angle between them and the 50% power factor (0.5 P.F.) test has the current lagging the voltage by $60°$. The watthour meter measures power between $90°$ and $270°$ in quadrants 1 and 4.

INDUCTION METER – The *Induction Meter* is a mechanical meter with a disk. Sometimes this type of meter is referred to as a "Ferrous Meter".

SOLID STATE METER – The *Solid State Meter* is a meter with no mechanical parts and uses electronic circuits to measure power. Sometimes this type of meter is referred to as an "Electronic Meter".

HYBRID METER – The *Hybrid Meter* is a mechanical meter that is fitted with a solid state (electronic) demand register.

PULSE INITIATOR – The *Pulse Initiator* is a device that can be attached to an induction or solid state meter that transmits contact closures as the meter measures energy. Each contact closure is equal to a defined amount of energy. These contact closures are known as *KYZ Pulses* and are typically used for recording the load profile or remote reading of the meter status. Mechanical pulse initiators used with induction meters have a fixed pulse value determined by a gear ratio between the disk and the device. Solid state meters have software programmable pulse values.

__LINE SIDE__ – The input side of the meter that is connected to the service entrance.

__LOAD SIDE__ – The output side of the meter that is connected to the customers load.

Appendix II: Computer Program

```
#include <iostream>
#include <math.h>

int main()
  {
   //input variables
   double i, v, n_cc, n_vc, r_cc, r_vc, x_cc;
   double x_vc, radius, r_disk, time, energy;

   //program variables
   double mu=4*3.1416*.0000001;         //mu is a constant and not entered
   double k, y, z, first, second, total;
          char again='y';


/*  Insert all the data--------------------------------------------------*/
  while(again=='y')                //can loop program for multiple runs
          {
          cout<<"Please enter Number of loops in the current coils:";
          cin>>n_cc;

          cout<<endl<<"Please enter the current (amps) used by the test load:";
          cin>>i;

          cout<<endl<<"Please enter resistance (ohms) in one current coil:";
          cin>>r_cc;

          cout<<endl<<"Please enter the distance (meters) between ";
          cout<<"the current coil and the disk:";
          cin>>x_cc;

          cout<<endl<<"Please enter the distance (meters) between the "<<endl;
          cout<<"center of the disk to the center of the voltage coil:";
          cin>>radius;

          cout<<endl<<"Please enter the resistance (ohms) across the "<<endl;
          cout<<"washer shaped eddy current path on the disk:";
          cin>>r_disk;

          cout<<endl<<"Please enter the number of loops in the voltage coil:";
          cin>>n_vc;

          cout<<endl<<"Please enter the potential difference (volts) of the load:";
          cin>>v;

          cout<<endl<<"Please enter the resistance (ohms) of the voltage coil:";
```

```
        cin>>r_vc;

        cout<<endl<<"Please enter the distance (meters) between ";
        cout<<"the voltage coil and the disk:";
        cin>>x_vc;

        cout<<endl<<"Please enter the amount of time (hours) the ";
        cout<<"test load is in use:";
        cin>>time;

        cout<<endl<<"Please enter the energy used by the test load:";
        cin>>energy;

/*  Math-----------------------------------------------------------------*/


        //first part of equation 24 in the mathmatical model
        y=mu*n_cc*i*r_cc*r_cc*radius;     //numerator
        z=x_cc*x_cc+r_cc*r_cc;            //parentheses
        z=z*z*z;                          //cubed then square rooted
        z=sqrt(z);                        //to get power of three-halves
        z=z*r_disk;
        first=y/z;

        //second part of the equation
        y=n_vc*v*r_vc*r_vc*time*3.1416*r_disk*r_disk;    //numerator
        z=x_vc*x_vc+r_vc*r_vc;                           //parentheses
        z=z*z*z;                                  //cubed then square rooted
        z=sqrt(z);                                //to get power of three-halves
        second=y/z;

         total=first*second;
         k=energy/total;          //using e.q. 24  k=energy/(mess of variables)

         cout<<endl<<endl<<"The disk constant is "<<k<<endl;
         cout<<"Run agian? (y/n) ";
         cin>>again;
         }
         return 0;
}
```

Appendix III: Sample Run

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