DUNCAN

Watthour Meters

Presents

Prof. Donald T. Canfield

in

"WHAT MAKES THE DISK GO AROUND"

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Sam Meyer - 10/11

"WHAT MAKES THE DISK GO AROUND"

With the use of simple models and charts, it is our intention to demonstrate the four basic essentials to the creation of an alternating current energy measuring device.

These four essentials will be covered in four steps as follows:

First, we must *DRIVE* the disk;
Second, *LAG* the potential flux;
Third, *DRAG* the disk proportional to the speed; and
Fourth, *RECORD* the measurement.

Induced Voltage

Our first problem is to DRIVE the disk. Suppose we start with a coil of wire wound upon a wooden spool and to which is attached a flash-light bulb. (Fig. 1). If this coil of wire is placed over the pole piece of an electromagnet which is energized by an alternating current, the lamp will light. Remove the coil and the light goes out. Note that there is no electrical connection between the coil and the energizing circuit. Yet the fact that the lamp lights is a positive indication that a voltage was present in the coil.

Michael Faraday, in the year 1831, was the first to demonstrate, or at least was the first to tell us why the lamp lights. He explained the presence of the induced voltage in the coil as follows:

The magnitude of the induced voltage is proportional to the number of turns of wire in the coil times the rate of change of flux threading through the coil.

Symbolically this statement may be expressed in the form of the equation:

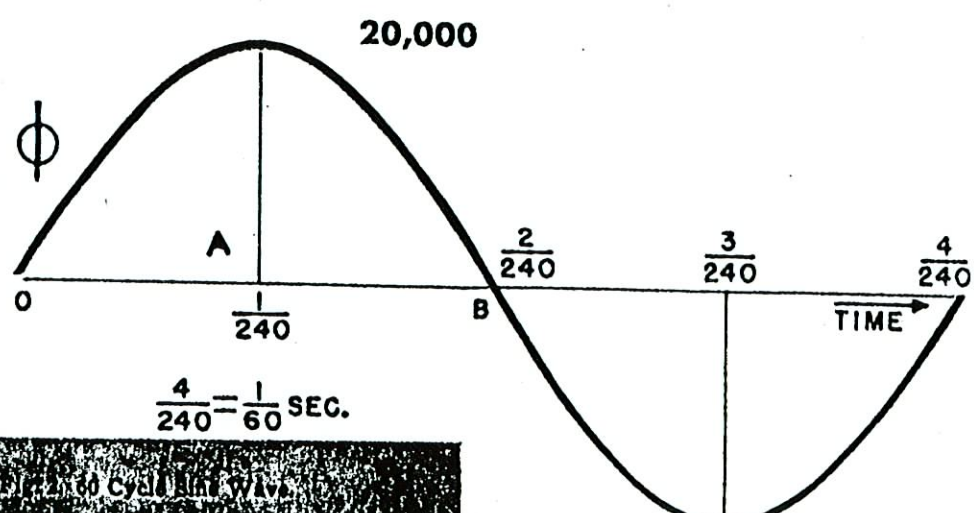
$$E = Kn\frac{\phi}{t}$$

where, E is the voltage,
K is a constant which enables us to express the voltage in volts,
n is the number of turns of wire in the coil,
ϕ is the flux, and
t is the time.

Now flux is the engineer's name for that invisible medium through which the force of magnetism acts. This force of magnetism can be shown by placing a common nail across the poles of the electromagnet. The engineer explains this action by imagining a bunch of invisible lines of force emanating from the pole of a magnet which he calls a magnetic field or magnetic flux, and he designates such fields of different strengths as having a larger or smaller number of these lines of force.

The rate of change of flux would then be the change in the number of these lines with respect to time. We can represent the rate of change of flux graphically as shown in Figure 2. Time is laid off to scale horizontally progressing from left to right. The magnitude of the flux, or the number of lines of force, is layed off to scale vertically, and its value is given by the curved line ϕ above and below the horizontal axis. In a 60-cycle source, such as is used here, the flux starts at the left at zero time, builds up to a positive maximum in 1/240 of a second and then returns to zero again in another 1/240 of a second. It then reverses and builds up to the same maximum in the negative direction after another 1/240 of a second. Finally, it returns to zero again in another 1/240 of a second and thereby completes a cycle in 4/240 or 1/60 of a second. If now we assume that the maximum value of the flux at instant *A* is 20,000 lines and that it reduces to zero at instant *B*, 1/240 of a second later, it is changing at the average rate of $\phi/t = \frac{20{,}000}{\frac{1}{240}} = 4{,}800{,}000$ lines per second. It is this rate of change of flux threading the turns n which produces the voltage E that lights the lamp.

If we should take a second coil possessing only half the number of turns of the first coil but connected to an identical lamp and place it over the pole of the electromagnet, the light would be dim since the voltage would be only half that of the first coil. If we should then, with the coil on the electromagnet, increase the flux by bridging the poles of the magnet with an iron bar, the light would immediately get



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brighter due to the increase in the number of lines that are threading the coil.

You might well ask, "What has this to do with a watthour meter?" The answer is, everything. In a watthour meter there is a disk mounted between two bearings which must be caused to rotate by placing it between the poles of electromagnets. (Fig. 3.) Voltage has to be induced in this disk, although there is no electrical contact between the disk and the electromagnets. How does any voltage get into the disk? By Faraday's principle. It is induced into it, just as it was in the coil a moment ago.

Currents and Ohm's Law

Now let's see what happens when a voltage is induced in the disk. Since the disk is a solid conductor, currents will circulate in the disk due to this voltage. The magnitude of these currents is directly proportional to the voltage and inversely proportional to the resistance of the disk. That statement you immediately recognize as Ohm's Law, first formulated by him in 1827.

This law is expressed symbolically by the equation:

$$\text{Current (I)} = \frac{\text{Volts (E)}}{\text{Resistance (R)}}$$

Ampere's Law or Forces on a Conductor Carrying Current in a Magnetic Field

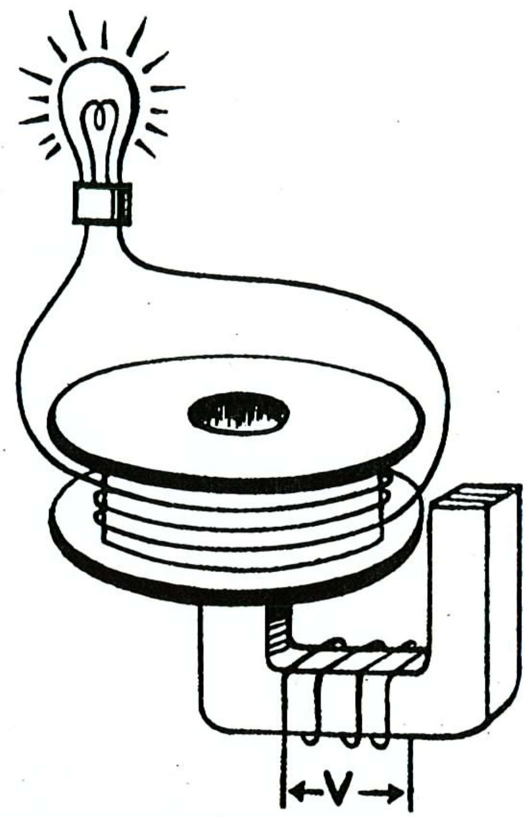
Now let us see what currents flowing in conductors can be made to do. In Figures 4 and 5 a copper wire is mounted on bearings in such a manner that it is free to swing between the pole pieces of two sets of alnico permanent magnets. If we pass a current through this conductor from left to right, as shown by a right hand deflection of the ammeter, the wire swings out. (Fig. 4.) If, however, we pass a current through the wire from right to left, as shown by a left deflection on the ammeter, the wire swings in. (Fig. 5.) Again, why? To answer that we must turn back to the year 1819 when Oersted first discovered that a conductor carrying a current in a magnetic field was acted upon by a force tending to move it out of the field. However, it was Ampere, who, a year later, formulated the law of this action. Expressed symbolically, it becomes the equation

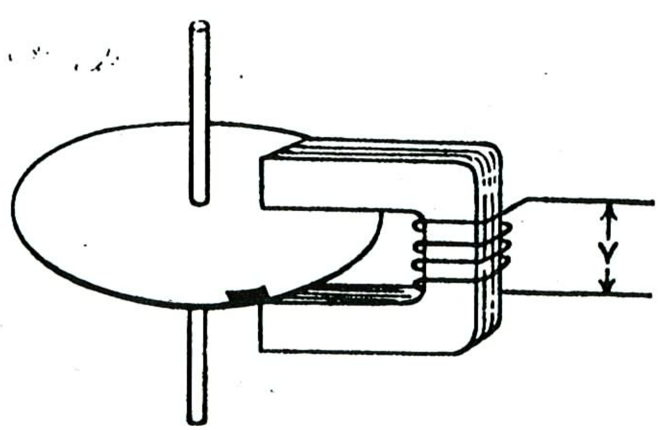
$$F = K \phi I$$

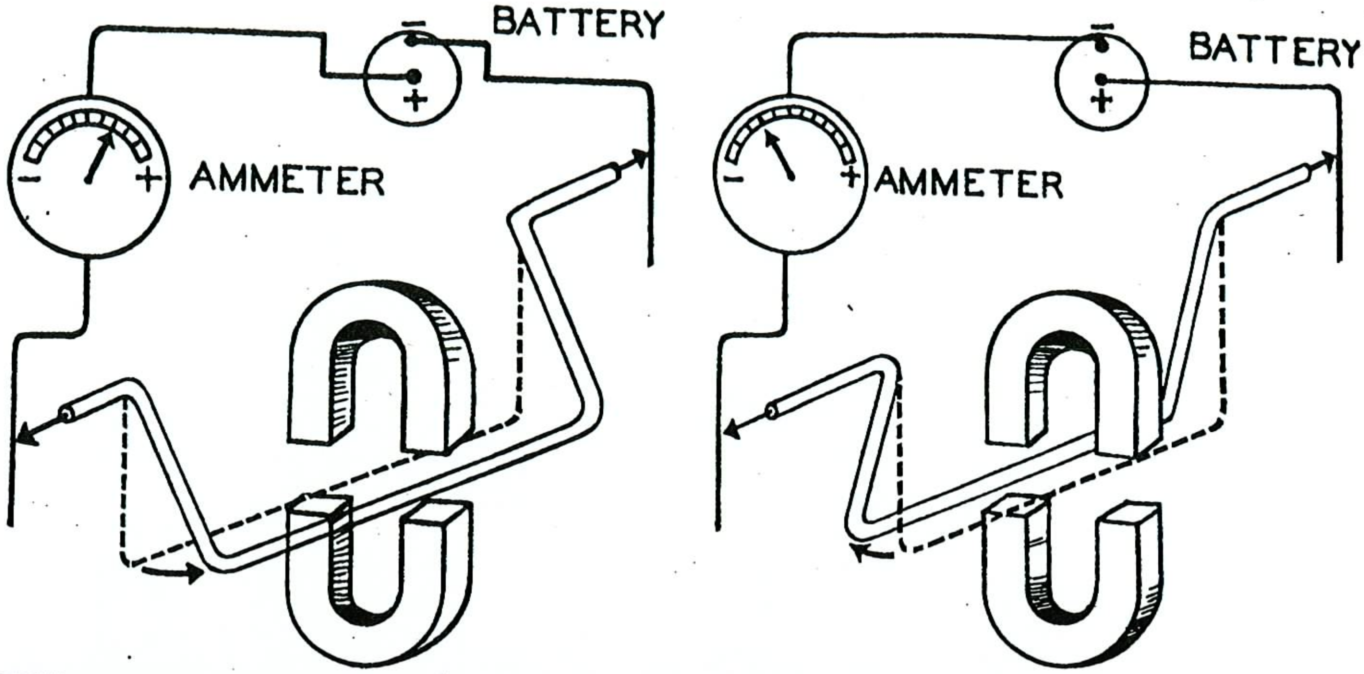
where, F is the force,
K is a constant,
ϕ is the flux coming from the magnets, and
I is the current in the conductor.

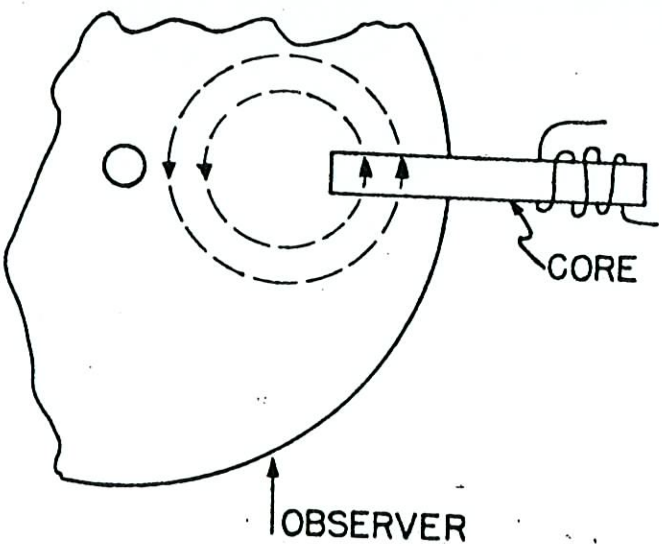
Since, in a watthour meter, the moving element is a disk and not a bar or wire, let us confine ourselves to the disk from now on. Suppose we energize an electromagnet from an alternating current source. That it is energized can be demonstrated by its action upon a common nail. If we place the disk in this magnetic field, (Fig. 3) there will be a voltage induced in it by Faraday's Law, and since the disk is a conductor, currents must flow in it by Ohm's Law. Thus we have a conductor carrying a current in a magnetic field, and by Ampere's Law there must be a force acting upon it, but, although the disk is free to rotate, it does not move.

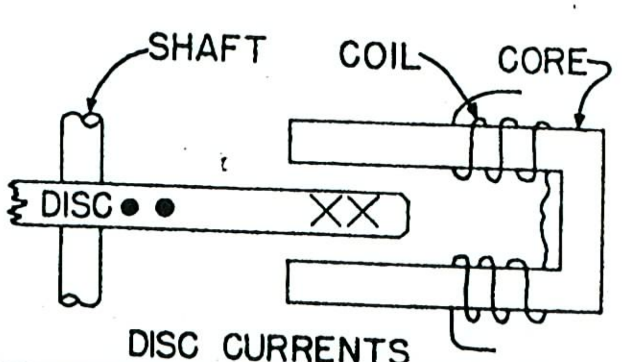
In order to explain why the disk does not move, it will be necessary to analyze a little more carefully exactly what is taking place in this situation. Unfortunately, we cannot actually see the currents in the disk and are therefore forced to represent them by lines. Figure 6 shows the section of the disk that is between the poles of the electromagnet. The currents in the disk are represented by the broken











circles and the direction of these currents by arrows. If we were able to see through the edge of the disk in the direction indicated on the Chart, we would see the points of the arrows coming towards us on our left, and the tails of the arrows going away from us on our right. In this manner we are able to show currents in a solid. The dots (•) mean that the currents are flowing towards us and the crosses (X) that the currents are flowing away from us.

Now consider Figure 7. The flux ϕ is varying with time according to the curve marked ϕ_1. The currents in the disk are varying along the same time scale according to the broken line marked *I*. Note that at instant *a* there is no flux, but there are currents in the disk as indicated by the dot and cross. Since there is no flux, one of the terms in Ampere's Law is zero, the product is zero, and therefore at that instant there is no force. Consider instant (*c*). At that instant there is a flux, but the current is zero, hence the product is zero, and again there is no force. At instant (b), however, there is present both a flux and a current and therefore a force, but there are in reality two equal forces. The product of flux and the right hand current tends to move the disk to the left while the product of the left hand current and flux tends to move the disk to the right with an equal force. The resultant force is again zero. Analyze the situation where you will and you will find that the net forces tending to produce motion are zero.

The Ferraris Principle

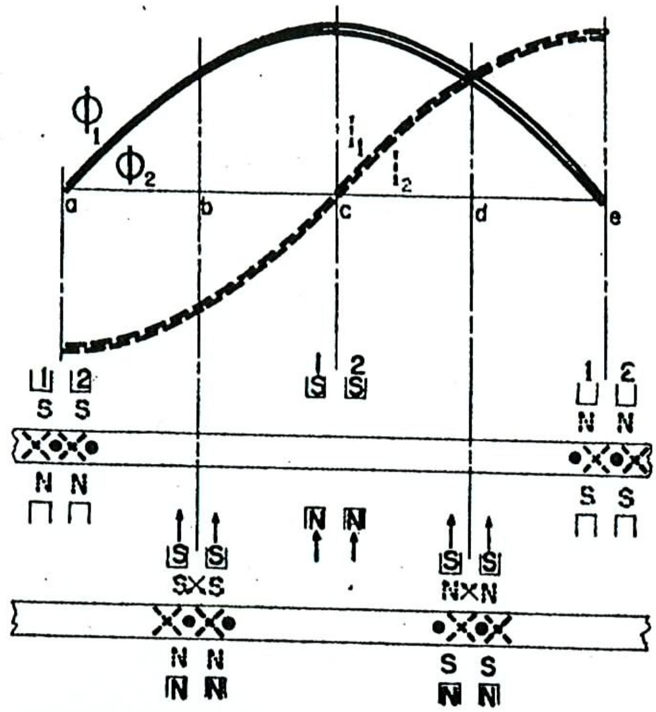
You know and I know that disks are made to revolve, but there was a lapse of just sixty-four years from 1820 to 1884 before anyone discovered how it could be done. The man who first conceived of the idea was Dr. Ferraris of Terrin, Italy, who opened the way to the development of the induction motor by Nikola Tesla in 1888 and all the other induction devices we have today including the watthour meter.

By means of a model, which he showed to his students at the University of Terrin, Dr. Ferraris pointed out that in order to produce motion electromagnetically, *two alternating current fluxes are needed which possess both a time and a space displacement in the direction of proposed motion.*

You will notice that two distinct things are required in concurrence—i.e., time displacement and space displacement. By time displacement is meant that the two fluxes must not attain corresponding values at the same instant of time as illustrated in Figure 8. Here the ϕ_1 and ϕ_2 fluxes vary along the time axis together. Therefore, there is no time displacement between them. However, in Figure 9, ϕ_1 and ϕ_2 fluxes do not reach corresponding values at the same instant. The flux ϕ_1 reaches its maximum positive value at instant (c) while the flux ϕ_2 does not reach its maximum positive value until instant (e). In this case 1/240 of a second or one quarter of a cycle later. This is what is meant by time displacement.

Space displacement results from the physical arrangement of the electromagnets that produce the two fluxes with respect to the disk. In the device shown in Figure 10, note that the two electromagnets are arranged around the circumference of the disk in such a manner that there is a space displacement between them in the direction of proposed motion of the disk. If we energize both electromagnets from the same source there is no motion.

If we try two fluxes that possess a time displacement but apply them in such a manner that there is no space displacement, which may be done by putting two coils on one core or putting the two electromagnets along a single radius of the disk, again there would be no motion. (Not illustrated.)



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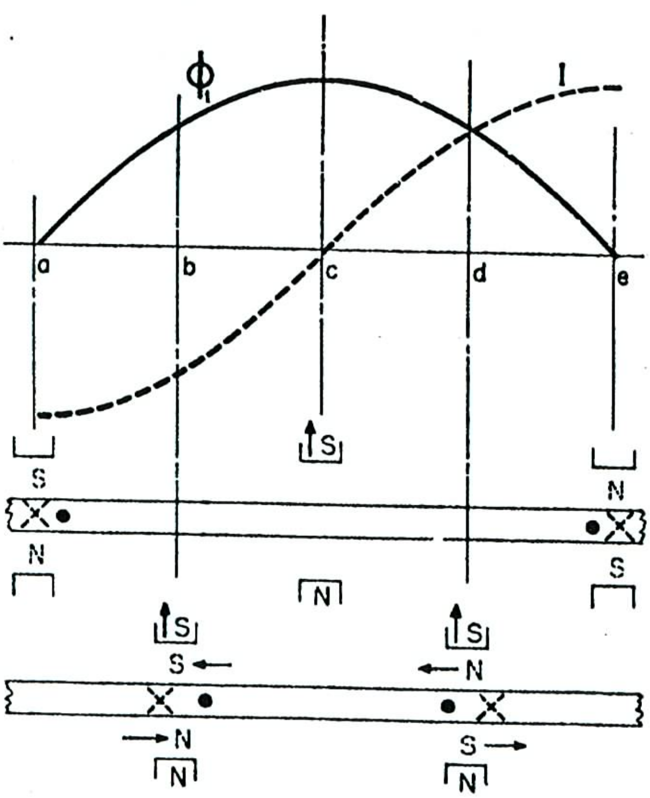

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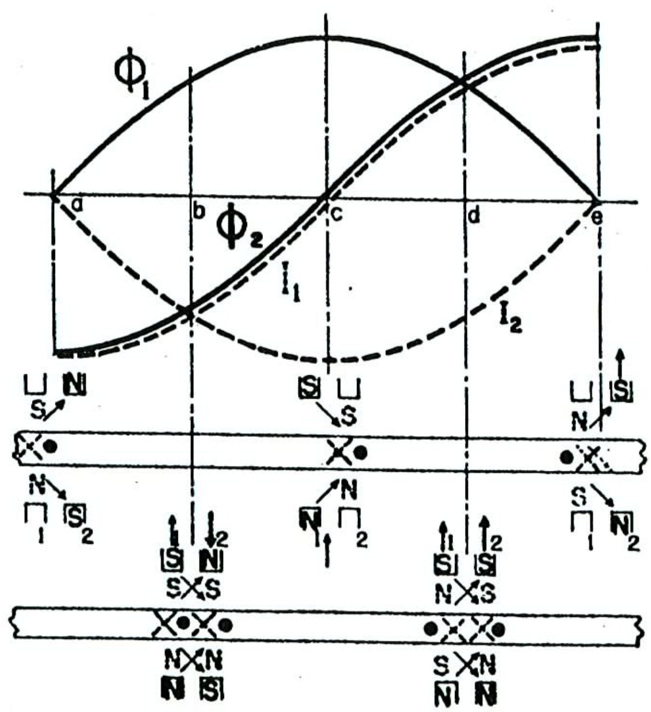

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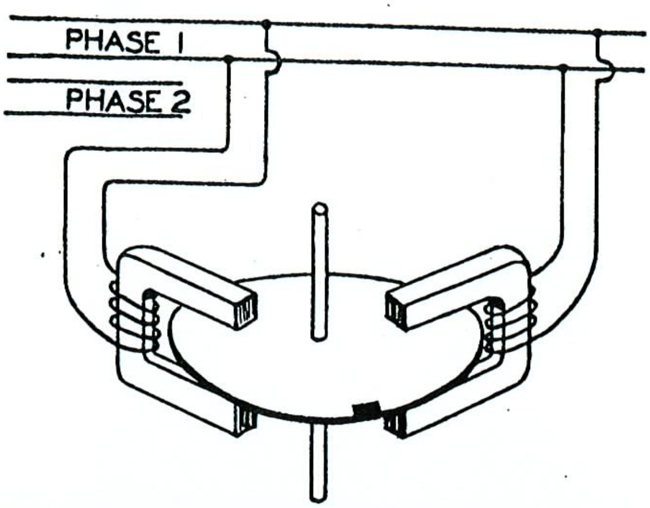

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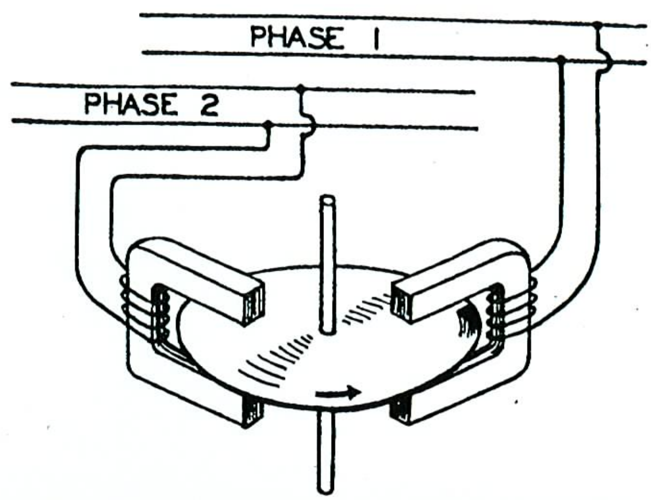

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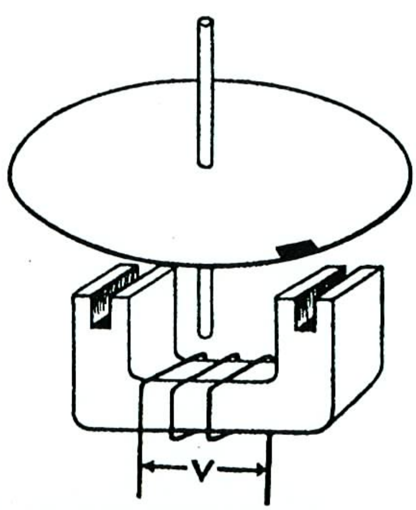
But suppose we do exactly what Ferraris told us to do—i.e., apply to our disk two alternating fluxes that possess concurrently, both a time and a space displacement, by energizing the left coil from phase 1 and the right coil from phase 2, which possesses a time displacement of ¼ of a cycle from phase 1. Then motion is produced (Fig. 11).

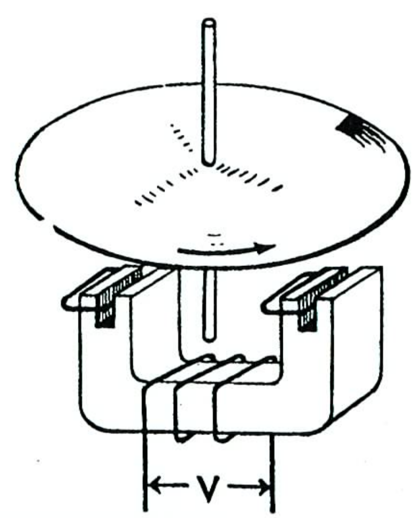
An analysis of the successful arrangement is given in Figure 9. The two fluxes ϕ_1 and ϕ_2 possess a time displacement of ¼ of a cycle. The two induced currents I_1 and I_2 are also shown in their proper time relation with each other and the fluxes that produce them. Below the time curves is shown the edge view of the disk and the electromagnet poles.

At instant *a* there is a flux ϕ_2 in the right hand electromagnet and a current, I_1, in the disk under the left hand electromagnet. This current will polarize the disk causing a south pole to appear above the disk and a north pole below. Since unlike poles attract each other, the south pole region above the disk will be attracted by the north pole of the right hand electromagnet and the north pole region below the disk by the south pole of the right hand electromagnet.

A similar analysis at instant *b*, *c*, *d*, and *e*, all show resultant forces tending to move the disk to the right. It is these forces, which for the first time are all in the same direction, which produce the motion demonstrated.

You have seen that varying time displacement varies motion. It will now be interesting to see what happens when we vary the space displacement. Assume a device is arranged, with one excited electromagnet above and one directly below the disk (not illustrated), producing considerable motion, and so that one electromagnet may be





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moved with respect to the other. Starting with this arrangement of excitation and position, if the upper electromagnet is moved to the right far enough a reversal of the disk takes place. There is a spot in between these two locations where no motion is produced. The same procedure can be repeated on the left side of the disk. A device very similar to this is used on sign-flashers to vary the rate at which the sign flashes.

The Shaded Pole Arrangement

Another application of the Ferraris principle can be demonstrated with the device illustrated in Figure 12. This energized electromagnet has a slot cut in the center of each pole piece. When the disk is placed over the pole pieces, there is no motion although there are two fluxes, one from each pole, and they are dispersed so as to give space displacement. There is, however, no time displacement between them and hence no motion.

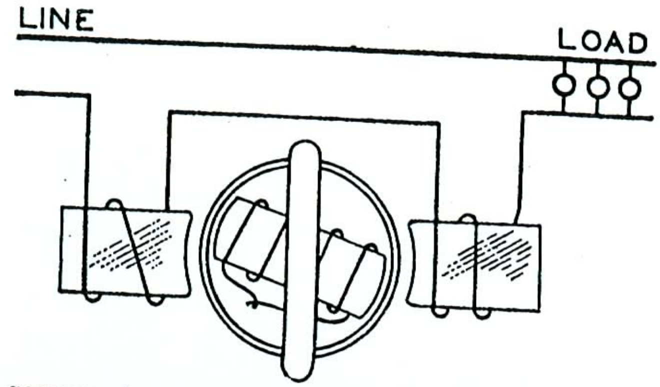
Now, if we take two short circuited copper loops and place them around half of each pole, using the center slot, motion is produced. (See Fig. 13.) The short circuited loops must have introduced the necessary time displacement. In fact, they actually caused the flux in their half of each pole to lag in time behind the flux in the other half. This process is often referred to as pole shading and is used in all electric clocks and many other devices. In a watthour meter it has a very important use which will be discussed later.

Shallenberger's Method

One of the earliest methods of producing motion was used by Oliver Shallenberger and Thomas Duncan as early as 1888. The method they used can be demonstrated with the device illustrated in Figure 14. It consists of an electromagnet which sets up an alternating current flux back and forth through the center of the device. This flux cuts a copper cup located between the poles and bearings. It also passes through an iron bar located inside the cup. Around this bar are wound several turns of bare copper wire all soldered together. The flux from the main electromagnet induces in these short circuited turns a voltage which causes a current to flow in them which sets up a second flux which inherently happens to be ¼ of a cycle in time behind the main flux. This second flux also cuts the cup, but no motion is produced if the bar is horizontal since both fluxes would cut the cup at the same spot and there would be no space displacement. If, however, the center bar is rotated slightly clockwise as shown, motion starts. If we rotate the bar slightly counter clockwise from the center a reversal of motion takes place.

Gutmann Method

One other application is of great historical interest to metermen. It concerns the arrangement used in the Gutmann meter built by the forerunner of the present Sangamo Electric Company. Gutmann attempted to design a meter that did not infringe the famous Tesla patents which patents claimed the Ferraris principle—all of it. In the Gutmann meter, the two electromagnets and the center shaft of the disk are very carefully lined up along a radius of the disk. In this arrangement there is no displacement of the two fluxes in the direction of proposed motion. Since he did not use space displacement of his fluxes, he was of the opinion that his device would not infringe the Tesla patents which claimed as essential this displacement. In order to get motion, however, Gutmann had to cut spiral slots in his disk so that the currents in the disk would be forced to move sidewise. That the idea works can be demonstrated



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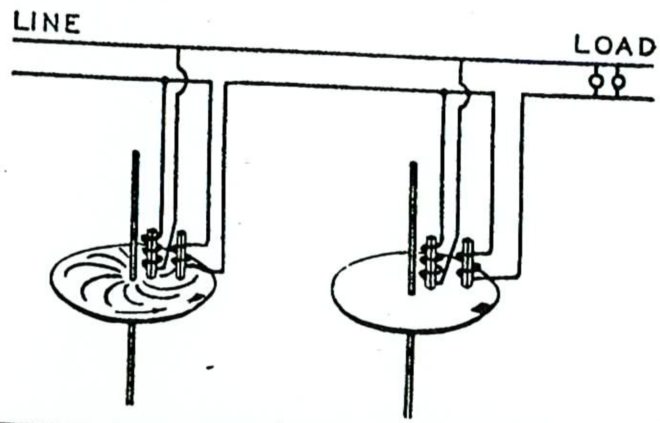

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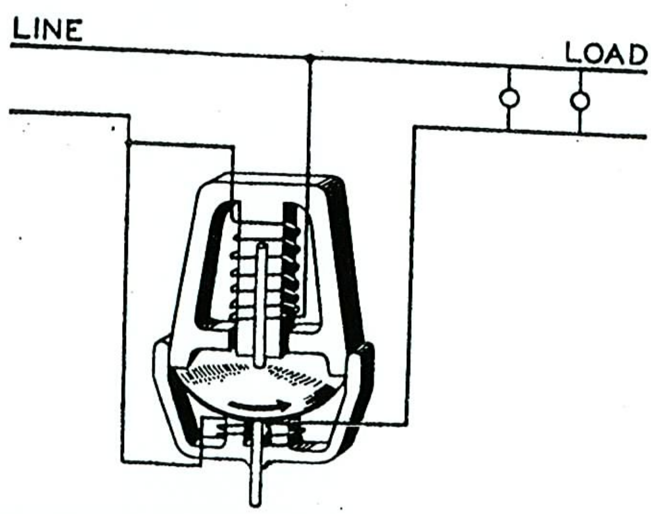

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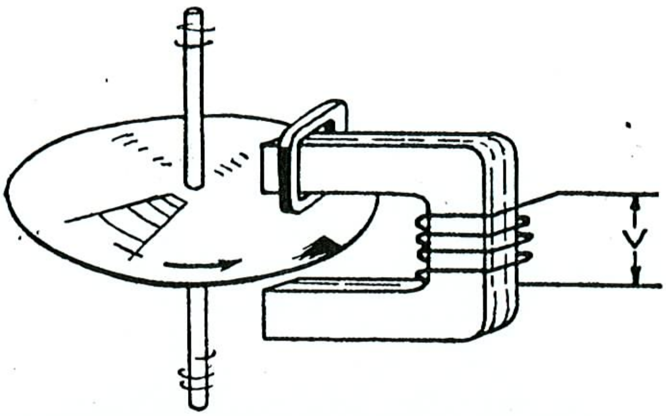
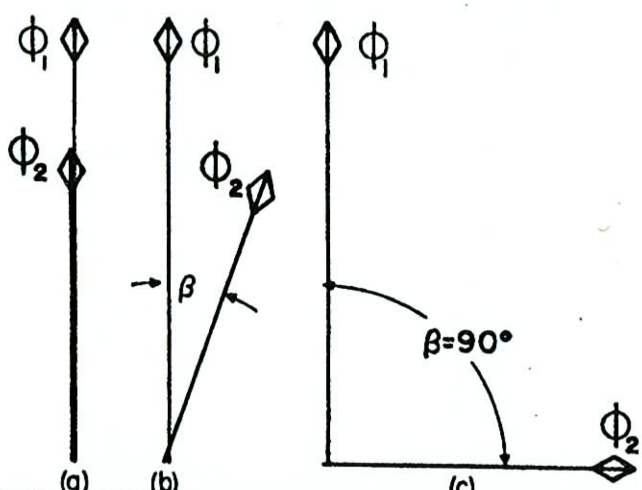
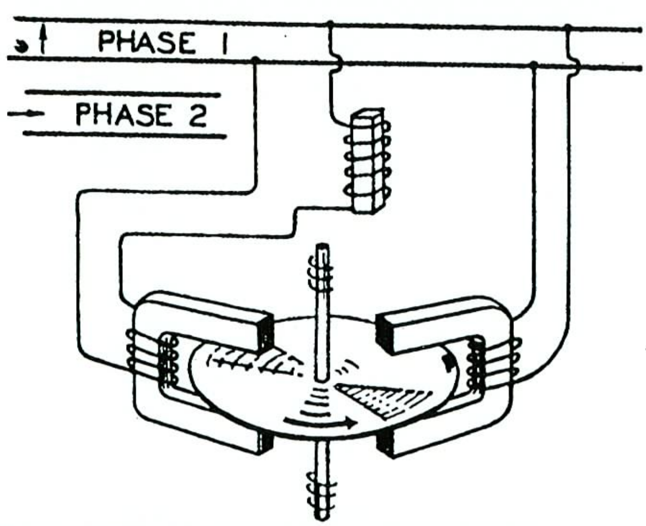






by using two identical Gutmann meters (Fig. 15) but placing in one of them a solid disk and in the other a Gutmann spiral slotted disk. When these meters are energized, the disk with the slots revolves while the other does not.

Modern Method

In an actual watthour meter of modern design the disk is caused to rotate by two electromagnets which generate two fluxes possessing both time and space displacement. A common arrangement is indicated in Figure 16. It is a very efficient driver of disks.

Friction Compensation

You metermen will be interested, no doubt, in the principle upon which the so called light-load or friction compensation adjustment operates.

You recall that the first device we used employing a single flux at a single point did not produce motion. We will, however, take a solid copper loop and place it around the pole of the electromagnet (Fig. 17). If the loop is moved slightly to the right, the disk moves in that direction. If it is moved to the left, the disk reverses and moves to the left. This very inexpensive and simple device can be and is applied to all modern meters and then adjusted with just enough eccentricity to offset the friction of the meter. This particular form of friction compensation was first applied by General Electric's Elihu Thomson.

The Magnitude of the Rotational Forces

Having completed Step No. 1, we proceed with Step No. 2—the lagging of the potential flux.

You have already seen what it takes to produce motion in a disk which is free to rotate. If, however, we are to build a device using this motion and capable of measuring electrical energy, we must do more than just cause a disk to rotate. It must revolve with a definite purpose, or as the engineer would put it, the force which causes the disk to rotate must be made directly proportional to the power flowing through the device at all times, in any amount, and under all conditions of loading. This means simply that, if the power is doubled, the force tending to produce rotation must be doubled; and if it is cut in half, the force must be cut in half.

We will now try to discover what this driving force is actually proportional to. You remember that two fluxes without a time displacement were incapable of producing motion. We may represent this situation by the first diagram (a) in Figure 18. If now a reactance coil is introduced into the circuit of one of the electromagnets (Fig. 19), motion is produced. The effect of the reactance coil must have been to introduce some time displacement, since that was the only element in Ferraris' principle that was missing. We may represent this slight amount of time displacement by introducing an angle β between the two fluxes as is done in the second diagram (b) in Figure 18.

Finally, if we introduce a time displacement of ¼ of a cycle, considerable motion is produced which means that considerable more force is exerted upon the disk. This result can be represented by the third diagram (c) in Figure 18, where the angle β has increased to 90°.

It follows that the amount of force exerted upon the disk has something to do with this angle β. In the first case when β was zero, there was no force. In the second case when β was small there was a small force, and finally when β was large (90°) there was a relatively large force.

Now to express angles of different sizes, mathematically we make use of a certain ratio called the sine. It happens that for β = zero, *sin* β = zero, for β greater than zero but less than 90°, *sin* β is greater than zero and less than one, and for $\beta = 90°$, *sin* $\beta = 1$.

Thus we may express the force on the disk by the equation

$$F = K \phi_1 \phi_2 \sin \beta.$$

where *sin* β varies from 0 to 1 as the angle β varies from 0° to 90°.

In Figure 20 is shown a load to which is applied a voltage E and through which is flowing a current I. The power delivered to the load is given by the expression:

$$P = EI \cos \theta$$

Where P is the power in watts, E is the voltage and I the current and *cos* θ is another one of these angle ratios which varies from 1 to 0 as θ varies from 0° to 90° and is called the *power factor*. It represents a time displacement between E and I just as *sin* β represents a time displacement between ϕ_1 and ϕ_2.

Our problem is to get the force on the disk

$$F = K \phi_1 \phi_2 \sin \beta = EI \cos \theta$$

To start we place one of our electromagnets across the load (see Fig. 20) so that the current in it will be proportional to E and therefore the flux created by it, say ϕ_2, will be proportional to E. We then take the other electromagnet and place it in series with the load. The current in it will be I and the flux created by it, say ϕ_1, will be proportional to I.

We can now draw a new diagram (Fig. 21).

In this diagram E is the voltage and I is the current with a time displacement θ from E. ϕ_I is created by I and is in time with it. ϕ_E is created by E but is out of time with E by a considerable amount due to the relatively high reactance of the potential electromagnet. With the electromagnets energized in this manner, the force on the disk will be

$$F = K_o \phi_E \phi_I \sin \beta.$$

Since ϕ_E is proportional to E we may substitute E for ϕ_E and since ϕ_I is proportional to I we may substitue I for ϕ_I; therefore, the force

$$F = K_o EI \sin \beta.$$

Making the Force Proportional to Power

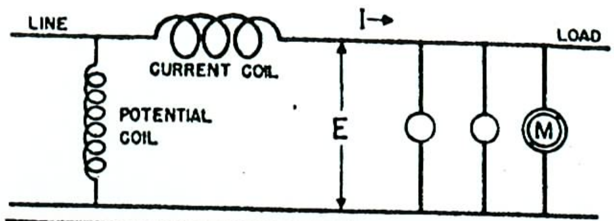
We now have to get EI sin β = EI cos θ. In the very early days of the art no one knew how this might be done. The first to discover how it could be done was Oliver B. Shallenberger, meter designer for Westinghouse, about 1894. Shallenberger pointed out that what was necessary was to cause the flux ϕ_E to move down till it was at exactly 90° to E. If this is done, the diagram of Figure 21 becomes the diagram shown in Figure 22.

Now we can write that $\beta = (90 - \theta)$ and our equation becomes $F = KEI \sin (90 - \theta)$. It can be proven that $\sin (90 - \theta) = \cos \theta$ and therefore we can write that: $F = KEI \cos \theta$, but since $EI \cos \theta = P$, it follows that

$$F = KP$$

when we do what Shallenberger did—i.e., move ϕ_E till it is at right angles to E.

This is probably the greatest single discovery ever made



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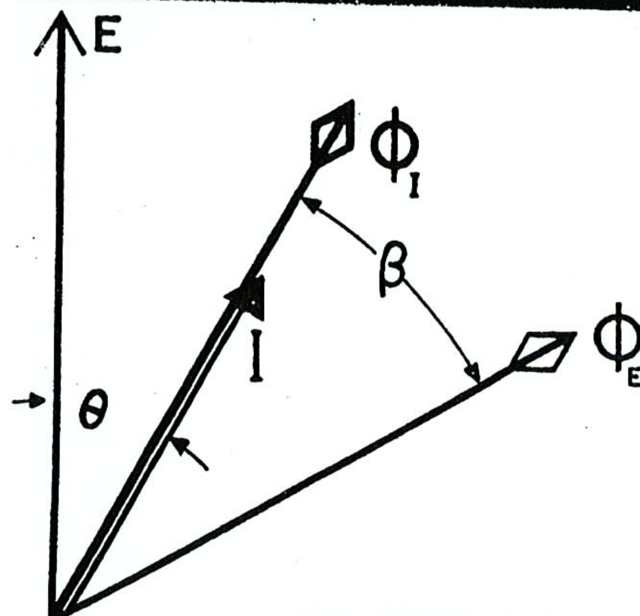

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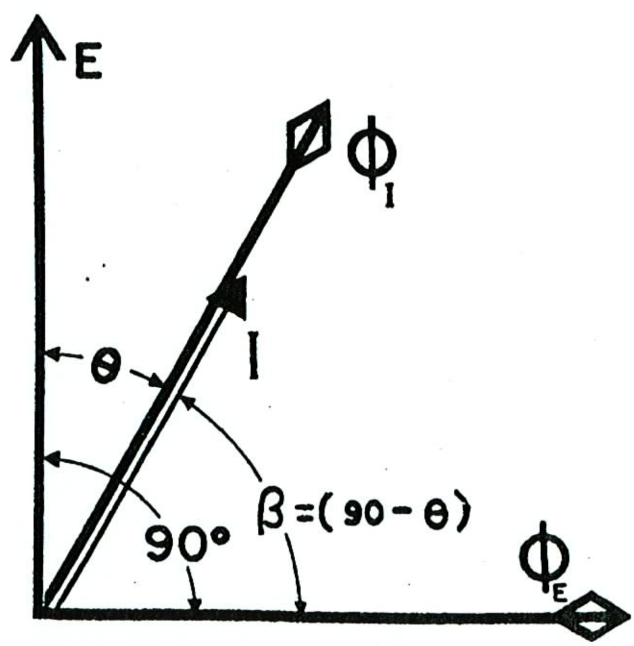

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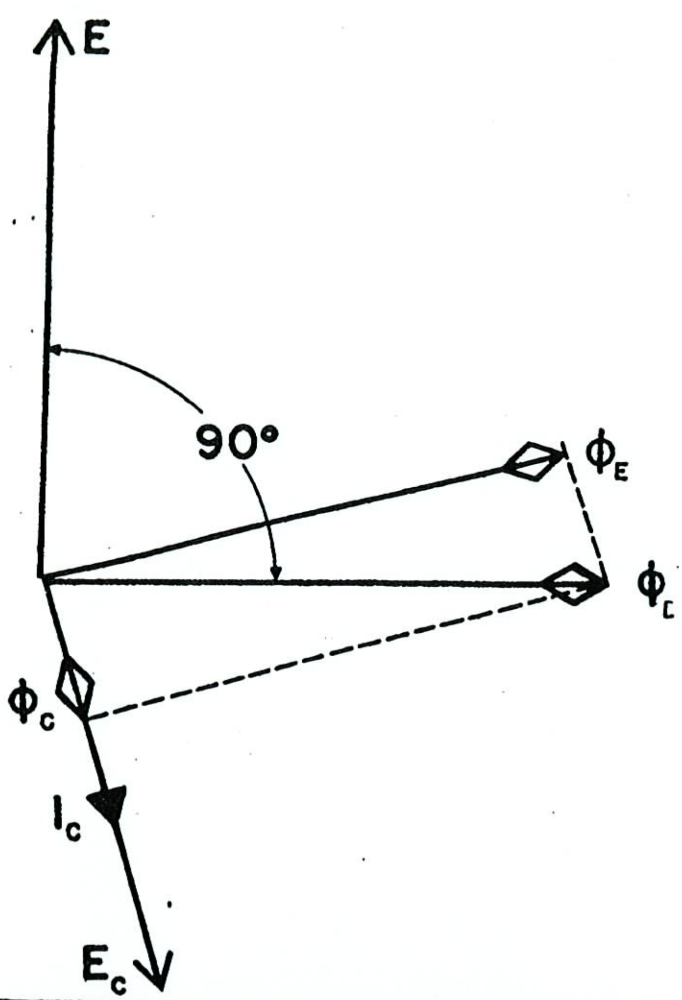

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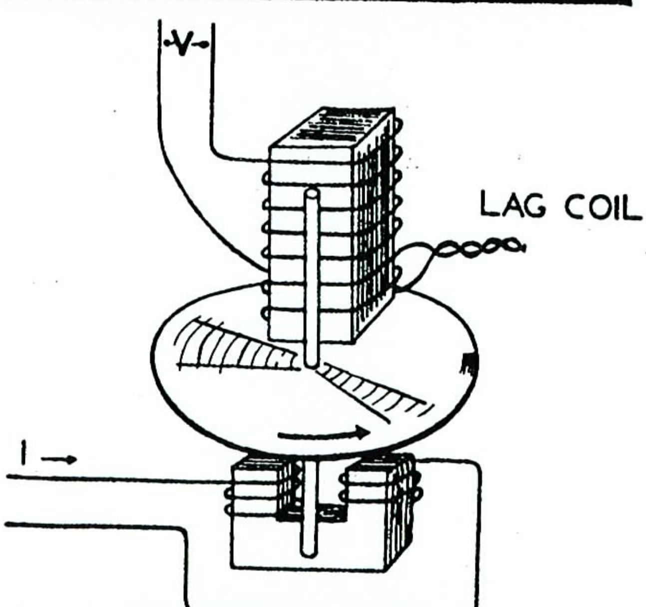

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in the art of measuring energy, as it opened the only possible way to the creation of an A.C. energy measuring meter, or the watthour meter as we know it today.

The process of causing ϕ_E to move until it is at right angles to E is known to metermen as the inductive-load or lag-adjustment. Figure 23 illustrates how it was done by Shallenberger and is still done by all manufacturers today.

If we place around the pole pieces of the potential electromagnet a short circuited loop or coil, (Fig. 24) ϕ_E will induce in it a voltage E_c. Since the loop is closed and conducting, a current I_c will flow in it. This current produces a flux of its own ϕ_c which, when combined with ϕ_E produces a flux ϕ_D that actually cuts the disk. The magnitude of ϕ_c may be varied by the conductivity of the loop until it is just large enough to make ϕ_D at right angles to E.

In most modern meters the potential flux is over lagged and a compensating lag adjustment is applied to the current electromagnet in order to improve the low power factor temperature characteristic of the meter.

Converting Power to Energy

Step No. 3 is to provide a DRAG on the disk.

With the force on the disk proportional to power as stated in the equation $F = KP$, it now becomes necessary to convert power to energy. The relation between power and energy is time. Power is a rate—the rate at which energy flows. Therefore, *power* multiplied by *time* is energy. It is analogous to miles per hour, where miles per hour times hours is miles. It follows that time must be introduced into our device. The process consists in applying to the disk an opposing or retarding force, the magnitude of which is proportional to the speed of the disk.

The disk, under the action of a force proportional to power, will attain some certain speed and run uniformly at that speed. The reason it will run at that certain speed is because all the forces which tend to produce rotation are exactly equal to all the forces which tend to oppose rotation. If either the driving or opposing forces are changed, the speed will change until there is again an equality between them. This is one of Newton's fundamental laws of motion, which if expressed in the form of an equation, becomes:

$$F_D = F_R.$$

If now we apply a retarding force to the disk, it will slow down. As will be proved later, a permanent magnet is capable of applying to the disk a retarding force proportional to speed, and when applied in a manner so that the moving disk cuts its magnetic lines of force, the disk immediately slows down. This slowing down is a positive indication that the force applied was a retarding force; and if we assume that the magnitude of this force is proportional to speed, we can write the equation

$$K_0P = K_1S$$

Since both sides of an equality may be multiplied by the same thing without changing the equality, we can write

$$K_0Pt = K_1St$$

Also, both sides of an equality can be divided by the same thing without changing the equality. If both sides of the above equation were divided by K_0 we would have

$$Pt = \frac{K_1 St}{K_O}$$

ɹut K_1/K_O is simply another constant, say K_h. Thus the the equation becomes

$$Pt = K_h St$$

However, *power* multiplied by *time* is energy and if P is in watts and t in hours, Pt is watthours. In like manner if S is revolutions per hour and t is in hours St becomes revolutions. Finally the equation becomes

$$\text{Watthours} = K_h \times \text{Revolutions}$$

Proof that a Permanent Magnet Retards a Disk with a Force Proportional to the Speed of the Disk
(This section referred to but not shown in film)

The disk is a conductor which is moving or cutting the permanent magnet flux ϕ. By Faraday's Law a voltage E_D will be introduced into the disk which is proportional to the product of the flux ϕ and the speed S. Therefore

$$E_D = K_2 \phi S$$

By Ohm's Law I_D due to E_D is given by the expression

$$I_D = \frac{E_D}{R_D} \quad \text{or} \quad I_D = \frac{K_2 \phi S}{R_D}$$

By Ampere's Law $\quad F_R = K_3 \phi I_D$

herefore $\quad F_R = \dfrac{K_3 \phi K_2 \phi S}{R_D}$

However, in a permanent magnet ϕ is constant, as is also R_D in any given disk. Lumping all of the constants in the above equation into a single constant K_1 we have

$$F_R = K_1 S$$

Evaluation of K_h

From the equation, Watthours $= K_h \times$ Revolutions, previously developed, it is seen that all that remains to be done is evaluate K_h and count the revolutions and we can measure energy.

K_h is the watthours per revolution of the disk. To evaluate it, it is first necessary to arbitrarily decide upon a suitable speed. Within reasonable limits the choice is purely arbitrary. Suppose we choose 30 R.P.M. when 600 watts is applied to the device. In an hour's time there will be 30 times 60 = 1800 revolutions, but one hour's use of 600 watts is 600 watthours. Therefore,

$$K_h = \frac{600}{1800} = 1/3$$

Thus, under the conditions selected, every time the disk goes around once, 1/3 of a watthour of energy has passed through the meter.

Counting the Revolutions

Finally, in the fourth step we must RECORD the measurement.

To count revolutions some form of a revolutions counter is required. The type of revolutions counter frequently

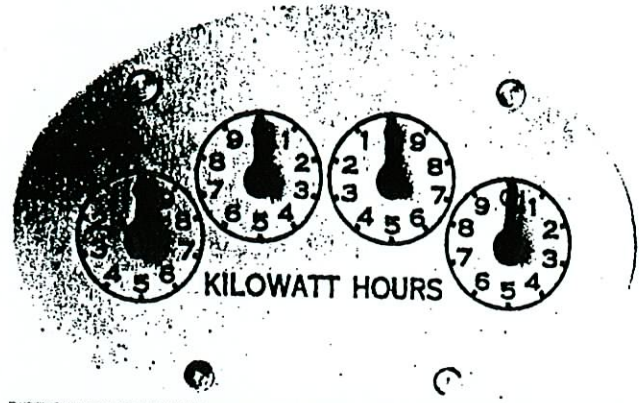
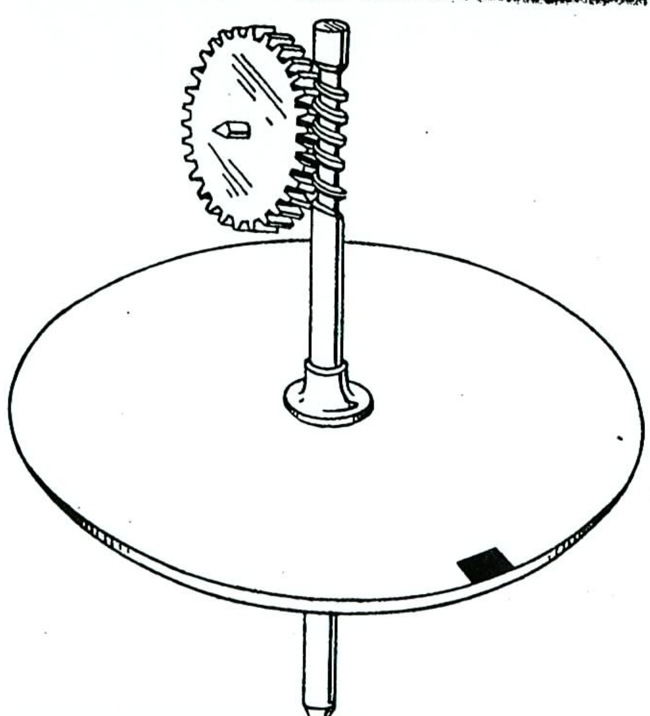


Fig. 25. Four Dial Meter Register or Revolution Counter

Fig. 26. Back View of Meter R[illegible]



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used for this purpose is the four dial and pointer combination shown in Figure 25. The first or units dial, in this counter, is calibrated in kilowatt-hours. A kilowatt-hour is 1000 watthours and one revolution of the first dial pointer records 10,000 watthours. On the other hand, as we see by equation $K_h = 1/3$ given above, one revolution of the disk is equivalent to only 1/3 of a watthour. There must, therefore, be a large gear reduction between the disk shaft and the first dial pointer. This reduction R_g will be:

$$R_g = \frac{10{,}000}{1/3} = 30{,}000 \text{ to } 1$$

So large a reduction in a single gear train would result in a device too big to be used in a practical meter. Consequently, in practice, it is done in two steps.

First, a single pitch worm thread is cut on the shaft of the disk and with it is meshed a 75 tooth gear (Fig. 27) (or other suitable ratio, depending on the manufacturer's design). This combination results in a reduction of 75 to 1 leaving for the revolutions counter proper a reduction R_r of only

$$R_r = \frac{30{,}000}{75} \text{ or } 400 \text{ to } 1$$

This latter reduction is called the register ratio and is customarily stamped on the register.

* * * * * *

Thus, in these four steps, we have demonstrated the principles of a watthour meter. The modern meter has many refinements and desirable features; but essentials—*NO*. No meter ever did more than the four essentials of *DRIVE, LAG, DRAG,* and *RECORD.*