Principles of electromechanical watthour meters

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Issue 2
February 4, 2024

ABSTRACT

For many years, the classical electromechanical watthour meter (typically in a glass "fishbowl" housing) was a fixture in every building that was a customer of an electric power utility company. It measured the cumulative energy drawn from the utility's "power grid" (as we say today) by the user's loads in the building, so the utility could bill the user appropriately.

Today most of these electromechanical watthour meters have been replaced by electronic watthour meters, which afford many benefits to the utility company.

But the principles on which electromechanical watthour meters operate are very ingenious, and fascinating. This article explains those in some detail.

Considerable background is given in some matters of physics and electrical engineering that play important roles in the story.

1 PREAMBLE

A watthour meter measures electrical energy, normally reading in the unit *kilowatt hour*, which corresponds to a power of one kilowatt (1000 watts) flowing for one hour.

These meters have many uses, but the one most familiar is reckoning the amount of energy consumed by a house, apartment, or business facility from the serving electrical utility company so the user can be billed for it.

The classical electromechanical watthour meter is thus a familiar sight. We have each had one at our house, or one of a bank of them in our apartment house, each in its own glass "fishbowl" housing.

This figure shows a relatively modern specimen of the genre (a GE Type I-70-S):

Figure 1. Modern electromechanical watthour meter

These meters operate on a very clever electromagnetic principle. This concept of the modern AC electrometrical watthour meter[1] was actually introduced in the 1890s. Of course, there have been numerous important advances in the construction and performance of these meters, but the central principle remains the same.

2 PHYSICS AND ELECTRICAL ENGINEERING BACKGROUND

2.1 Introduction

In this section, before getting to our actual topic, I will review certain principles of physics and electrical engineering that are fundamental to the measurement of the electric power flowing through a circuit.

2.2 Units

The SI[2] unit of power is the *watt* (W), the unit of voltage is the *volt* (V), and the unit of current is the *ampere* (A). Energy is the time integral of power. Thus the conceptual SI unit of energy is the watt-second (the amount of energy conveyed by a power of one watt over a time of one second), but that unit actually has is own SI name, the joule (J). (More on this a little later.)

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[1] Watthour meters for use on DC power circuits use a quite different principle.

[2] This refers to the International System of Units (abbreviated SI from the initials of its French name), the "modern metric system".

2.3 In a DC circuit

I first note that in a "pure" DC circuit the voltage and current (at least over a short period of our interest) are constant. That having been said, the power flowing from a source into a load in a DC circuit is given by:

$$P = VI \tag{1}$$

where P is the power, V is the voltage across the load, and I is the current through the load. I use upper-case letters here to indicate that these are unchanging values (unchanging at least over a perhaps short period of observation).

Since P is unchanging, it is also the average power (over the period of our interest).

The energy provided into the load over some period is the time integral of the (instantaneous) power; thus:

$$E = \int_t P\,dt \tag{2}$$

where E is the energy conveyed over the period of interest. Substituting from Equation 1 into Equation 22 gives:

$$E = \int_t VI\,dt \tag{3}$$

Of course with P constant over the period of interest, that becomes, for period T:

$$E = TP = TVI \tag{4}$$

2.4 In an AC circuit

Here we recognize that the voltage and/or current are continuously changing during even a short period of our interest, perhaps following a "sine wave" pattern at some frequency (as we typically assume, at least for the voltage, for AC power distinction situations).

The instantaneous power at some specific instant is given by:

$$p = vi \tag{5}$$

where the lower-case letters indicate that these are instantaneous values.

Although in electronic circuit design and some other areas we are indeed concerned with the instantaneous power, when speaking of the power consumed by some load device (a toaster, perhaps), our interest is in the time average (time mean) power (averaged over some period of time, perhaps only one cycle of the AC waveform), thus:

$$\bar{P} = \overline{(vi)} \tag{6}$$

where the overbar signifies the mean of the quantity beneath (that this is the *time average* is implied by the context).

(For an AC circuit, the average power is generally written, except in equations, and often even there, as just P.)

And if we are concerned with energy (perhaps in that we have to buy it from a power utility), we again find that energy (over some perhaps long period) is the time integral over that period of the average power, or:

$$E = \int_t \bar{P}\,dt \tag{7}$$

But since the (long term) time integral of the (short term) time average of some value is the (long term) time integral of that value itself, this becomes

$$E = \int_t p\,dt \tag{8}$$

which of course can be expressed as

$$E = \int_t vi\,dt \tag{9}$$

2.5 The "practical" unit of electrical energy

As I noted above, the SI unit of energy (electrical or otherwise) is conceptually the compound unit watt-second, which, in the SI, has its own name, the joule (J),

But in the world of buying and selling electrical energy, the customary basic unit is the watt-hour. And thus it is no surprise that the energy meters I speak of here are called "watthour[3] meters". Since there are 3600 seconds in an hour, it follows that one watt-hour is 3600 joules.

Of course, even though the watt-hour is not an SI unit, it still admits of the use of SI multiple prefixes. Because of the quantities involved in the reckoning of energy in the context I mention, the unit in which a

[3] It is the custom in that field to spell this compound unit as one word.

typical watthour meter reports the energy flow through it is the kilowatt-hour[4] (kWh). One kWh is 1000 watthours (1000 Wh), and so is 3.6 megajoules (3.6 MJ). Meters for us when very large amounts of energy are involved are often scaled to read in megawatt[5] hours.

2.6 Electromagnetism

2.6.1 *The magnetic field around a current-carrying conductor*

If we pass an electric current though a conductor, a magnetic field[6] is created around the conductor, the "lines" of magnetic flux (it is of course fanciful to think of their being "lines") curling around the conductor.

If we wind a number of turns of the conductor around a tube (creating a "coil winding", the "lines" of flux created around each turn of the conductor are gathered, leading to a substantial amount of flux flowing through the inside of the coil (and, in fact, longitudinally along its outside as well, just not as "concentrated" there).

2.6.2 *Voltage induced in a moving conductor in a magnetic field*

If we have an electrical conductor lying along the **x** axis in space, and we have a magnetic field in the **y** direction, and we move the conductor in the **z** direction, a voltage is induced in the conductor.

This is the principle of the classical rotating electrical generator.

2.6.3 *The Lorentz force*

If we have an electrical charge moving along the **x** axis in space, and we have a magnetic field oriented along the **y** axis, then a force is exerted on the charge along the **z** axis. This force is named after the famed Dutch physicist Hendrik Lorentz, whose work was pivotal in understanding this phenomenon.

It of course operates when the charge is one electron of the zillions traveling along a conductor carrying a current, in which case the result is a force on the conductor.

This is the underlying mechanism of most types of electrical motors.

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[4] It is the custom in that field to spell that as "kilowatt hour" (no hyphen).

[5] Be now you get the drill.

[6] Sadly, "magnetic field" is used in the literature to denote two quite different, although related, quantities, one mathematically designated **B**, and the other **H**. But sometimes here I will allow the term to remain ambiguous, where that does not hurt the story I am telling.

3 THE BASIC CONCEPTS OF WATTHOUR METER OPERATION

3.1 Operation as seen from 30,000 feet

The heart of an elctromechanical watthour meter is its *motor*, a special type of AC induction motor. It receives two electrical inputs, the voltage across the power line and the current through it. The motor turns at a rotational speed proportional to the short-term average of the product of the **instantaneous** line voltage and the **instantaneous** line current. That product is the **instantaneous** power through the line into the load at any instant.

Thus the rotational speed of the motor is proportional to the short-term average power flowing into the load. And so the total rotation of the motor over some period is proportional to the energy flow through the meter during the period.

The rotation of the motor is directed, through a gear train of appropriate overall ratio, to a system of dials (the "register") that displays, in decimal form, the amount of energy that has passed through the meter (usually since it was "commissioned").

The difference between that reading at the beginning and end of a utility company "billing cycle" (typically, about a month) tells the amount of energy consumed by the user during that period.

3.2 A little closer look

Now we will look at the meter's motor a little more closely.

The voltage across the line passes through the winding of a *voltage coil*. The current through the line passes through the windings of two *current coils*. Both are on a magnetic core through a gap in which which passes an aluminum disk, the rotor of the motor.

The electromagnetic interaction of the two sets of coils generates an instantaneous torque on the aluminum rotor disk that is proportional to the instantaneous power flowing through the meter at any instant. The inertia of the rotor effectively averages (on a short-term basis) the effect of that torque on the rotation of the rotor.

The rotor disk also passes through the magnetic field between the pole tips of a powerful permanent magnet. This creates a torque resisting the rotation of the rotor, whose magnitude is proportional to the speed of rotation of the disk.

The result of these two effects on the rotor disk is that, for any "short term" average power passing through the meter, the rotor settles into a dynamic equilibrium at a rotational speed proportional to the average power.

The rest of the story is as described just above.

4 DETAILED OPERATION OF THE METER MOTOR

4.1 Preamble

In this section I attempt to give a through but hopefully easy to follow explanation of the principles of operation of the motor portion of the classical electromechanical watthour meter. In doing so, I will sometimes de[part from complete rigor as to some of the details involved, to prevent the discussion from being too lengthy.

The model by which I lead the reader through this operation is rather idealized, with a strict forward-acting chain of cause-and-effect stages. In reality, the matter is more subtle than that. But I ignore that in the interest of clarity of the concepts involved.

4.2 The AC power circuit

For most of the discussion I assume a watthour meter configured to operate on a 120 V single-phase AC power supply circuit. By doing so, I avoid some complicating distractions.

After we have in hand the operation of such a meter, I will move to the use of a meter on a 120/240 V single-phase AC circuit (as is usually found in the typical residence or small business situation).

4.3 A first look at the motor

This figure:

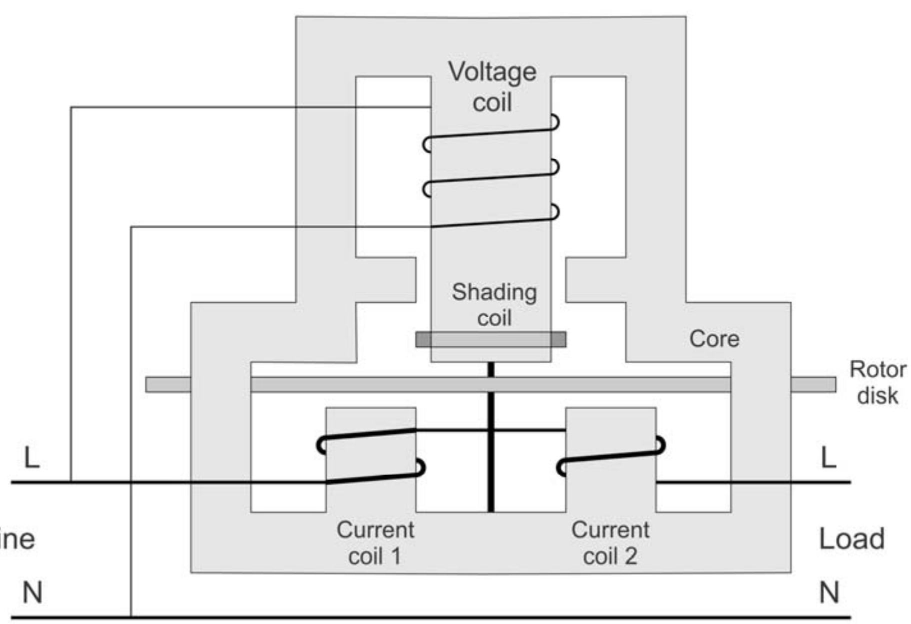

Figure 2. Watthour meter motor

shows in schematic form in "elevation" view the construction of the central part of a typical electromechanical watthour meter motor, in place in an AC power circuit of the type just described, with many of its components and features labeled. This part is sometimes called the *stator* of the motor.

That power circuit itself comprises a line ("hot") conductor, L, and a neutral conductor, N.

The *core* is made of thin steel laminations, much as for a typical transformer. It is provided with three wound coils. The *voltage coil* is connected across the incoming power line, from L to N. The two *current coils* are themselves in series, in series with the "hot" lead of the power line (L) as it passes through the meter. The nature and role of the shading coil will be described later.

The rotor of the motor is a thin circular aluminum disk on a shaft running in low-friction bearings (perhaps even being magnetically suspended). Its shaft is a bit behind (in the view of the illustration) the plane of the core; that is, the core pole tips all fall on the outer portion of the rotor disk nearest us. (We will get a better view of that relationship in another figure, shortly.)

Not shown in this figure is a powerful permanent magnet, whose pole tips close on a thin gap, through which the part of the rotor disk farthest away from us passes. We will see it later.

4.4 How the motor actually works

In will do this in several stages, some of which are (for clarity of illustrating the principle) portrayed as simple but which in reality have various subtleties I will not discuss just now (many of them I won't discuss at all).

4.4.1 *The work of the voltage coil*

I will start with this figure:

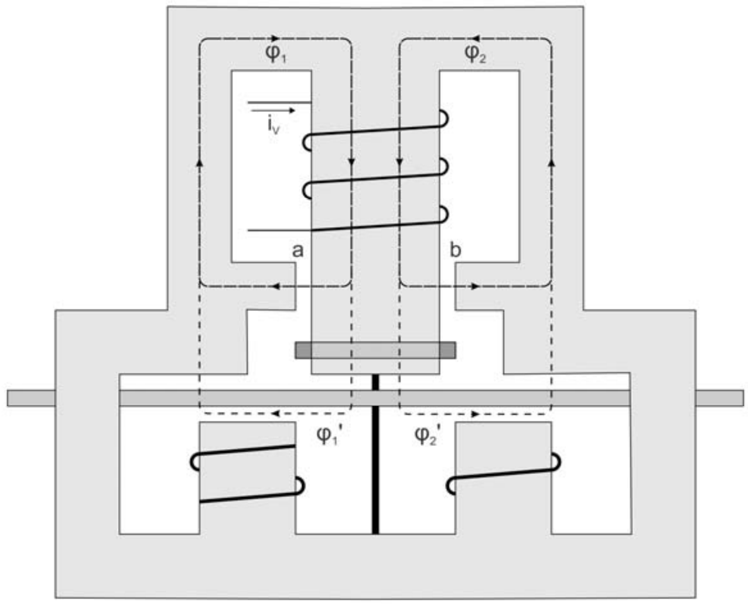

Figure 3. Result of current in the voltage coil

Although the voltage coil is energized by the *voltage* appearing on the power circuit, I will start by considering the resulting *current* through the coil, as that is what creates the magnetic phenomena of which I will speak. I designate that current i_V, the subscript referring to the voltage coil. The use of the lower-case letter implies that this is an instantaneous value.

That current creates a magnetic field[7] which in turn causes the creation of a magnetic flux, φ, which is the flow[8] of the "stuff" of magnetism.[9]

That flux divides into two equal streams, φ_1 and φ_2, which follow the two paths broadly represented by dashed lines.

Most of the flux in each of those two streams crosses the small gaps (labeled "a" and "b") adjacent to the central leg. Only a minor fraction (φ_1' and φ_2',) goes down the center leg, where it passes through the rotor disk. That latter portion returns to the overall circuit magnetic through a fairly lengthy and indistinct air path (suggested by the lower dashed lines).

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[7] In one sense of the term, which "field" is denoted mathematically as **B**.

[8] The word "flux" actually means "flow", so whenever possible I avoid the temptation to say "the flow of flux". But sometimes I just can't help myself.

[9] That flow of flux (excuse the tautology) is itself a magnetic field in the other sense, which field is denoted mathematically as **H**.

Why would we want the preponderance of the flux generated by the current through the voltage could to just “recirculate” (through gaps **a** and **b**) and not even report to the battle zone at the rotor disk? The reason for that is best explained later, so for now just recognize that this is how the thing is made.

This next figure is a top view of that we have seen so far. It is in part to show the relationship of the core and coil assembly (represented by the dashed rectangle) to the disk. We see the circular disk itself (well, most of it) and a representation of its shaft.

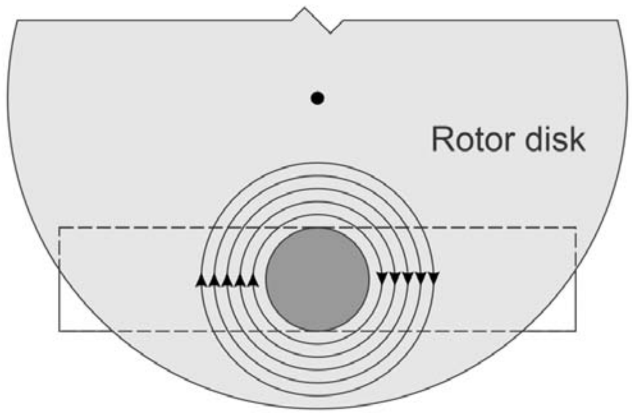

Figure 4. Top view: voltages and then currents induced in the rotor

But it also shows (in an unrealistically tidy way) what the flux coming through the central leg of the core does in the disk[10]. The rate of change of that flux causes the induction of voltages in the disk in circular paths around the core pole tip. Those voltage patterns in turn create a swath of current flow in an identical circular pattern[11]. This is represented by the circles with directional arrows.

4.4.2 *The work of the current coils*

Now we return to our “elevation” view of the structure:

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[10] I have shown that pole tip as having a circular cross section; it might in reality be square with rounded corners.

[11] Such currents induced in a metal body (for example, in the core of a transformer) by a changing magnetic flux are often called “eddy currents”, by parallel with the “eddies” that occur in water in some situations. I will use that term here.

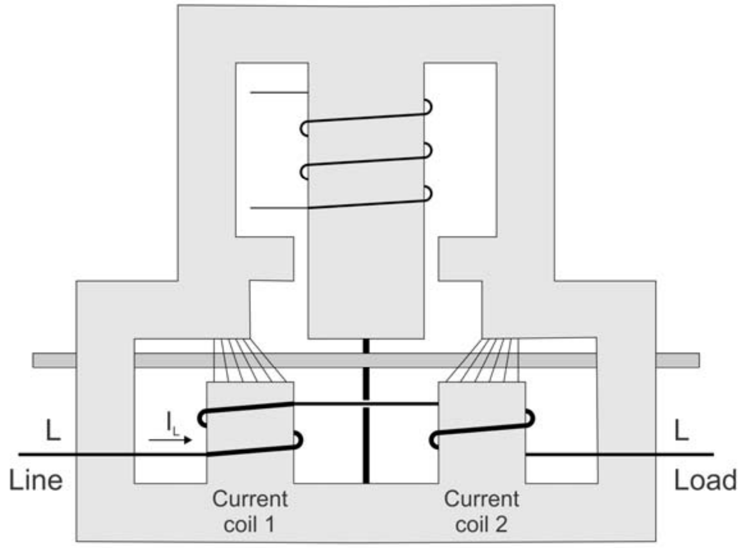

Figure 5. Currents in the current coils

We will assume that those "eddy currents" are still present in the disk, even though they are not represented in this figure.

The line current, i_L, flows through both the current coils. At each, that causes a magnetic field to be created in the air gaps above the pole tips. The light lines fancifully suggest that magnetic field[12].

Note that the "poling" of the two coils is such that, for a given instantaneous current, the direction of the flux is opposite for the two coils. We will see shortly why that is appropriate.

Now we go back to our overhead view:

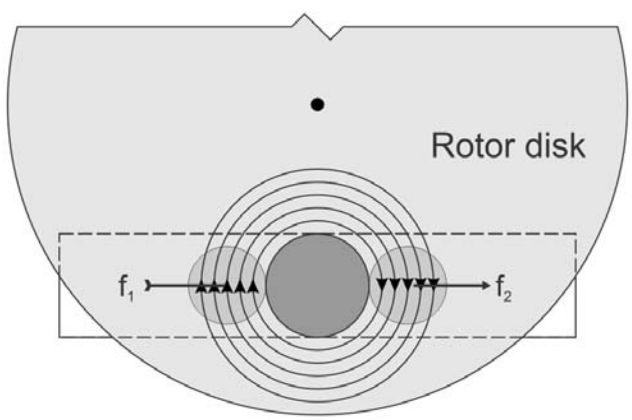

Figure 6. Effect of the current coils

[12] Yes, indeed, there as a flow of magnetic flux there, caused by that magnetic field. Thus there is a confusing duality here that I discuss in section 7.

The lightly-shaded circles represent the pole tips of the current coils (below the disk) and also magnetic field existing from those pole tips from those pole tips up through the disk.

The interaction of the current flow in the disk with the magnetic field represented by that flux from the current coil pole tips causes a force on the disk In the direction shown by the straight arrows in figure 6. For the directions shown for the various quantities, that force is to our right from both the left and the right current coil pole tip fields (because the polarities of the two current coil fields are opposite, but so are the directions (in their regions) of the eddy currents, with which they interact in a multiplicative way.

Those two forces, acting at a distance from the disk shaft, each create a torque on the rotor (counterclockwise as seen from overhead).

That torque on the disk is proportional to the instantaneous power through the meter.

4.4.3 *The stator in reality*

This figures shows a typical watthour meter stator:

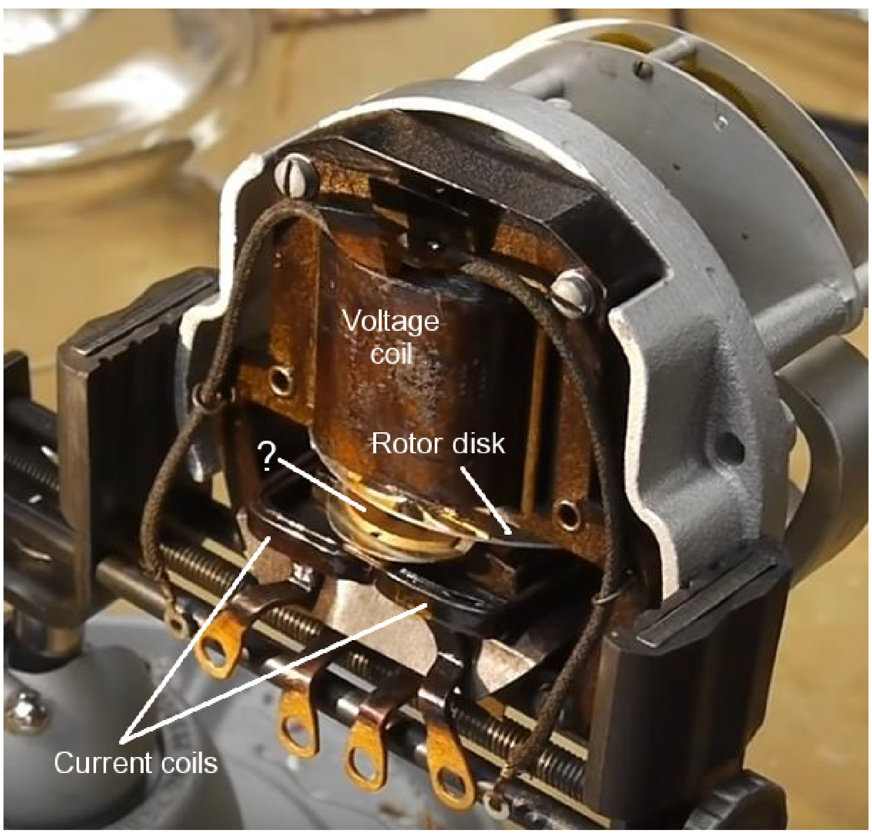

Figure 7. Watthour meter stator

The four fat ring terminals at the bottom are the terminals of the two paths through the current coils. In a “plug-in” style meter, they go to the four “prongs” that connect to the “jaws” of the meter socket.

The smaller ring terminals are on the flexible leads from the voltage coil. They will connect to the two “input” prongs of the “plug”.

I have no idea what the object labeled with a question mark is. It is not part of the stator, and is in place once the stator has been removed.

4.4.4 *The permanent magnet*

Now we use a different view so we can see another of the prominent players, the *permanent magnet*.

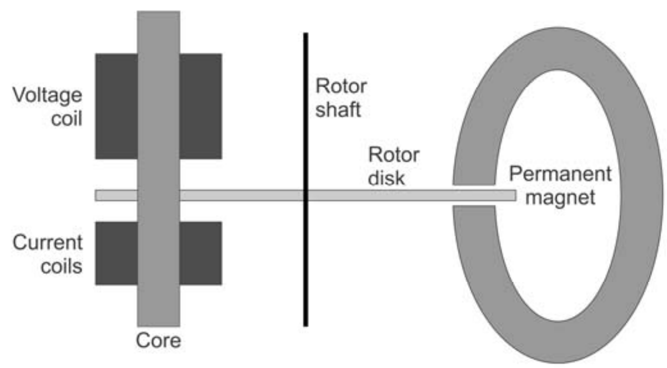

Figure 8. The permanent magnet

We see that its pole tips form a narrow gap, within which the outer portion of the disk lies.

There is a strong magnetic field in the region between the pole tips.

As the disk rotates, the movement of its outer portion through that magnetic field induces voltages in the part of the disk that is directly under (and near the) pole tips. This in turn causes the flow of eddy currents in that part of the disk.

Those eddy currents then interact with the magnetic field, resulting in a circumferential force on the disk. Its direction is unavoidably counter to the direction in which that part of the disk is moving—a *retarding* force, which results in a retarding torque on the disk.

Because the voltage induced in the disk is proportional to the rate of movement of the disk material, the induced current is similarly proportional, and the retarding force (and thus torque) is also proportional to the speed of movement of the rim, and thus to the rotational speed of the disk.

So we have these two things occurring:

- We have a "forward" torque on the rotor disk that is proportional to the short-term average of the power through the meter.
- We have a "backward" (retarding) torque that is proportional to the rotational speed of the rotor disk.

The result is that, for any short-term average power through the meter, the disk settles into a dynamic equilibrium in which its rotational speed is proportional to the power flow. And, ensuite, the total rotation of the rotor disk over some period is proportional to the total energy flow through the meter during that period.

For convenience in explaining the principle, in figure 8 I showed the permanent magnet of a traditional shape in a handy position. In reality, the magnet is often actually two magnets, arranged as we see (from overhead) in this figure:

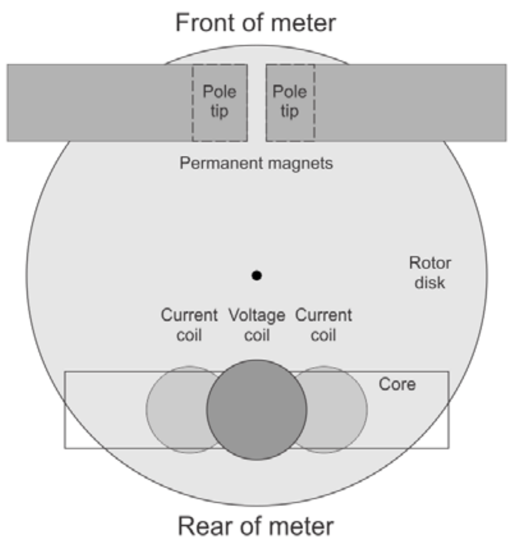

Figure 9. Permanent magnets, more realistic—front view

By the way, In a typical actual meter, as noted on the figure, the stator is at the rear, near the "prongs" by which the meter plugs into a socket to connect it into the power line. And thus the permanent magnet is toward the front, typically just behind the meter "nameplate".

In further reality, often the shapes of these permanent magnets are usually quite different than shown in the figure (although identical in concept and function), usually to best fit in the available space inside the meter's glass housing while still clearing the rotor disk.

We see one example of that in this figure, of the innards an "antique" GE model I-20 watthour meter:

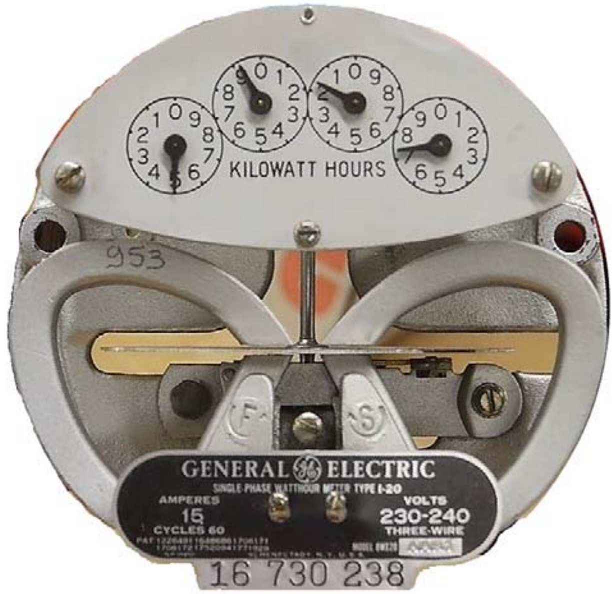

Figure 10. GE Type I-20 meter—dual permanent magnets

However, in more modern times, it is common to have the two magnets integrated into one “bowtie” unit, as we see in this figure.

Figure 11. GE model AC5 watthour meter—“bowtie” magnet

Even more modern meters, though, may have only a single small meter, perhaps located to one side of the disk (made possible by advances in the “potency” of permanent magnets.

We see that in this figure (this is actually the same meter model as seen in Figure 1):

Figure 12. GE I-70-S meter—single magnet

The permanent magnet is on the right of the rotor disk.

Because the relationship between the power through the meter and the rotational speed of the rotor is directly affected by the strength of the flux field created by the permanent magnets, we can change that relationship to "calibrate" the meter by changing the exact amount of that flux.

One way this is done by having a movable member that shunts some of the magnetic flux generated by the permanent magnet away from the gap within which the rotor disk operates, or in some other way affects the amount of that flux. This member is usually moved by small screw. The resulting change in flux in turn affects the calibration of the meter.

We see an example in Figures 11 and 12, where the screw head is accessible though the meter nameplate. There are two arrows representing the two directions the screw can be turned, marked "F" (for faster) and "S" (for slower).

4.4.5 *About phase relationships*

In section 4.4.1, I said I would at first concentrate on the current through the voltage coil (not the voltage across it), since it is that current that is the beginning of the magnetic phenomena I described.

I also mention that the instantaneous voltage induced in the disk by the voltage coil is proportional to the rate of change of the magnetic flux, and thus to the rate of change of the current in the voltage coil.

But the long story In told earlier clearly intimates that the magnetic field from the voltage coil must remain at all time proportional to the instantaneous voltage on the power circuit. How do we reconcile those two seemingly incompatible facts?

Firstly the voltage coil has not only resistance but as well a substantial inductance. The inductance is great a result of the fact that the preponderance of the flux generated by the current in the voltage coil has an almost closed path through the core (interrupted only by the small gaps “a” and “b” seen in figure 3).

So we now see the motive for letting most of the flux just circulate around, only allowing a small fraction of to actually go through the disk: this makes the coil have a fairly high inductance.

The voltage across a pure inductance is proportional to the rate of change of the current through it (the first derivative of the current). So, conversely, the current through a pure inductance is proportional to the integral of the applied voltage.

But, from calculus, we know that, for a sinusoidal function of time, represented by a cosine function[13], its integral is represented by a sine function. And a sine function is just the cosine function **delayed** by exactly 1/4 cycle (we speak of this as 90°). So the waveform of the current thorough the voltage coil is behind the waveform of the voltage across the coil by 90°.

Now the voltage induced in the disk is proportional to the rate of change of the flux through the disk (that is, proportional to the first derivative of the current through the disk).

But, from calculus, we know that, for a sinusoidal function of time, represented by a sine function, its first derivative is represented by a cosine function. And a cosine function is just the sine function **advanced** by exactly 90°. So the waveform of the voltage induced in the disk thorough the voltage coil is ahead of the current across the coil by 90°.

[13] Note that “sinusoidal” refers to a waveform having the shape of a sine function, but not necessarily the sine function itself. For example, a cosine function has the same shape as a sine function (albeit with a different time alignment), so a waveform described by a cosine function is still said to be “sinusoidal”.

Thus (if the coil is a pure inductance) the voltage induced in the disk is in phase with the voltage applied to the coil. And the eddy current in the disk is proportional to that induced voltage, so it too is in phase with the voltage across the coil.

So, again assuming that the voltage coil is a pure inductance, at any instant the instantaneous current in the disk will be proportional to the instantaneous voltage across the voltage coil (the instantaneous line voltage). This is exactly what is needed for our theoretical concept of power measurement to work as I have described. (It is better to be lucky than good!)

But we are not quite that lucky, for the voltage coil is not a pure inductance. Its impedance also includes significant resistance (primarily the resistance of the wire with which it is wound).

So the waveform of the current though it will not be quite 90° behind the voltage waveform. Still, the rate of change of the current through it (and thus the voltage induced in the disk) will inevitably be 90° ahead of the current (required by facts of calculus).

The result is that the waveform of the voltage induced in the disk will “lead” the line voltage waveform by a small amount. That small discrepancy is enough to spoil the model we described as how the rotor measures power, and thus energy flow.

Overcoming this is the job of the *shading coil* (which we saw in figure 2 but not since, it remaining hidden until I was ready to discuss its action). We see it in place here:

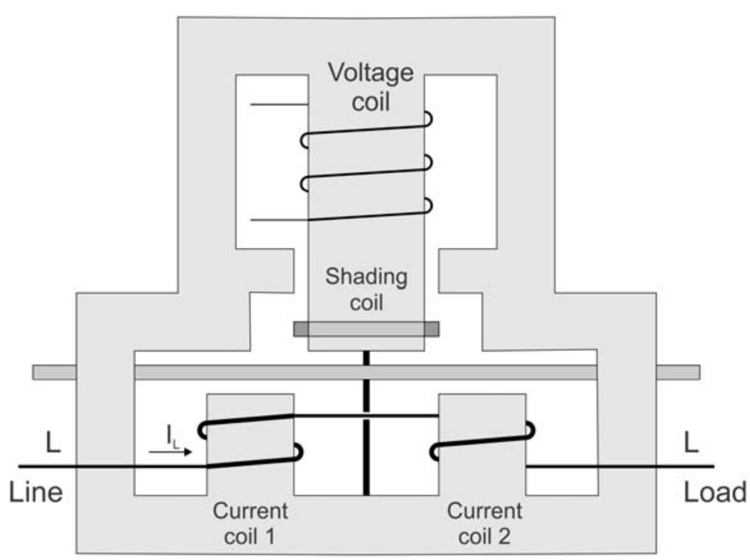

Figure 13. The shading coil

It is just a thick copper ring surrounding the voltage coil pole tip. It is in effect a single turn, short circuited, “secondary coil”.

The flux in the pole tip induces a voltage in the shading coil, that being instantaneously proportional to the rate of change of the flux (and thus whose waveform is 90° ahead of the waveform of the flux).. That induced voltage causes a current to flow in the shading coil, which in turn creates its own flux.

But this flux is proportional to the current in the shading coil, whose waveform is 90° **ahead** of the flux created by the current in the voltage coil. Those two flux components combine to form the flux actually passing though the rotor disk.

If the properties of the shading coil are just right, the result is that the voltage induced into the rotor disk by the voltage coil will be exactly "in phase" with the voltage across the voltage coil (the voltage of the power circuit), just what we need.

In fact, often there are provisions for moving the shading coil along the pole tip to vary its influence on the overall system, in order to attain that ideal situation (as the meter is "calibrated" in the factory or at a field calibration depot.

4.5 Nonlinear loads

Note that for the theoretical principle of these maters to be fulfilled, we must have very nearly a sinusoidal waveform for the voltage to the voltage coil (the line voltage). And in fact, that is ordinarily very nearly so.

Bust as to the current coils, the instantaneous magnetic field they generate is directly proportional to the instantaneous current through them, there being no intermediate maneuvers dependent on the presumption of a sinusoidal waveform.

So in fact the overall plan will work even of the line current waveform is not sinusoidal. And that is a good thing, for today many loads (electronic circuit devices) have in fact "nonlinear" current vs. voltage behavior, which means that when they are given a sinusoidal waveform of voltage, the current waveform might not be sinusoidal.

This even extends to loads whose current vs. voltage response is asymmetrical, meaning that there is a "DC component" to their current waveform. The current coils are as willing to generate a flux waveform with a "DC component" as otherwise.[14]

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[14] It is often (but erroneously) believed that if we were to construct a large load with a rectifier diode in series, so that there would be a large DC component to the current drawn, much if the energy consumed by that load would not be "counted" by the watthour meter. No such luck.

4.5.1 *Compensating for friction*

Notwithstanding such clever schemes as supporting the rotor disk shat in magnetic bearings, there remains some friction in the overall mechanical system. This produces a very small error in the meter's operation, but one large enough that it cannot be neglected considering the very tight standard of precision expected of these meters.

To minimize this error, most watthour meters are equipped with an arrangement on the pole pieces of the voltage coil (essentially, a plate that constitutes a "shading coil") that produces, so long as the voltage coil is energized (and imagine that there is no current in the current coils) a secondary magnetic field of such a phase that it interacts with the eddy currents induced in the stator disk to produce a very small torque in the "forward" direction. The intent is that this will just be enough to overcome the small frictional torque.

Typically, that plate is movable so as to shift the magnitude or phase of this secondary magnetic field, thus adjusting the amount of torque produced. This is adjusted in the factory or a meter calibration depot until the counter torque is just enough to overcome the system friction.

This is sometimes referred to as the "light load" adjustment. In fact, the adjustment is usually made not to assure that the disk is stationary at zero load, but rather so that the meter reads correctly with a very small (and precisely known) load applied.

4.5.2 *Creep*

Of course, the balance between the frictional resistance and the torque produced by the scheme just described can shift over time. In some cases, the torque prevails (although of course just slightly) The result is that, with zero current in the current windings (all loads off) the rotor disk may still move very slowly (it will "creep"),

This is of course produces a second-order error, so small as to be wholly acceptable under the accuracy standards. But the homeowner concerned that the watthour meter may be malfunctioning (and thus resulting in the bill from the electric utility to be "outrageous"), may shut off all the loads in the house and then look at the disk in the watthour meter. (The disk in fact has a fat black mark at one place near its edge so it can easily be seen if it is moving.[15])

[15] This is actually there mainly to facilitate meter calibration, which may involve careful timing of the disk's rotation.

And aha! With no loads the meter is still moving! So the electric utility gets a complaint call, and they have to explain what that is from which is not easy.

To avoid this distraction, most watthour meters have an anti-creep feature. At one or two places around the outer edge of the rotor disk there is a small hole. When this comes under the polepiece of the voltage coil, this disrupts the normal formation of the eddy currents in such a way that a (tiny) counter-torque is produced that overcomes the (tiny) "creep" torque and forces the disk to remain in that position. It is rather like a very weak electromagnetic "detent" [16].

Of course, as soon as there is any consequential current in the current coils (from any consequential load), a forward torque is produced that easily overcomes this "detent" action (the momentum of the disk, now rotating at a non-trivial speed, helps that), and the meter does its work as expected.

5 THE REGISTER

5.1 Introduction

Of course, the ultimate role of the meter motor is that its rotation is totted up into a readable accumulated energy indication, which occurs on the assembly called the *register*. In most cases (especially in the US), this gives its reading on a number of dials with pointers. We see this in Figure 1 and Figure 11, but more close up in Figure 14.[17]

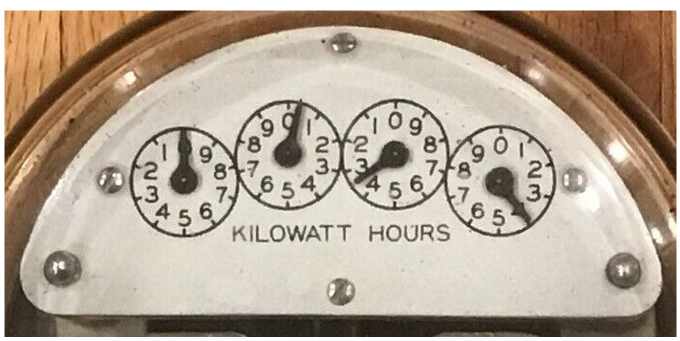

Figure 14. Sangamo Type J2A watthour meter—register dials

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[16] However, we must be careful about the term "detent" in this area, since, inexplicably and illogically, it is used to describe a special feature of watthour meters used in some special situations, a behavior that is actually not "detent-like" at all.

[17] An alternate form of register, almost universally used on watthour meters in Europe, looks like a traditional mechanical automobile odometer, called in this field a *cyclometer* register. That name in turn comes from the fact that odometers of this sort were first used on bicycles.

We see a typical register, and the gear train by which the motor drives it, here.

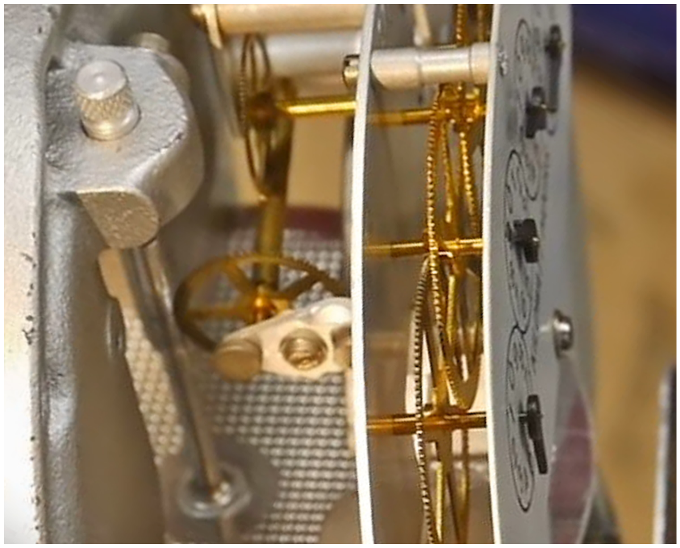

Figure 15. Register and drive gearing

Note that the rotor disk shaft drives an intermediate countershaft through a worm drive. That countershaft then drives a second countershaft through another worm drive. That countershaft drives the "units" dial pointer shaft through a pair of spur gears (not visible in this figure)

This figure shows this arrangement schematically:

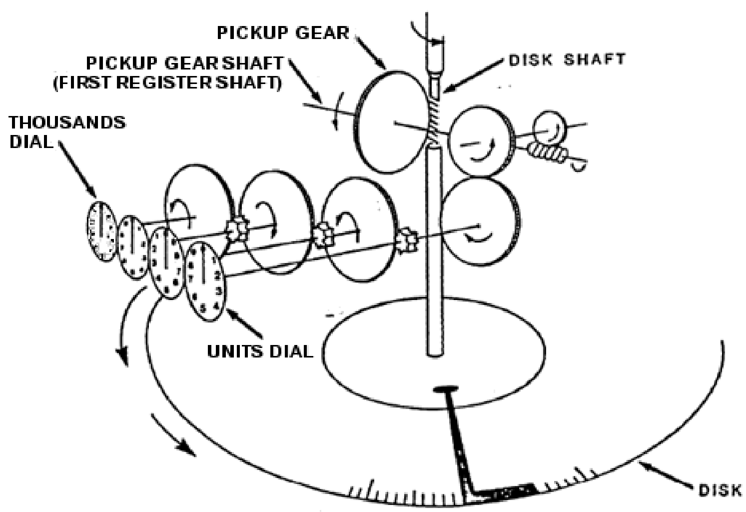

Figure 16. Register gearing

Unlike the "drums" in an odometer, here the successive dials are just simply geared together with a 10:1 ratio in each stage. That brings about these two "curiosities":

- Alternate dials turn in alternating directions (as we can see from the direction of increase of the number value labels on the various dials in Figure 1 and Figure 11).

- If, for example, the "units" dial is at 5, then on the "tens" dial, the pointer will not be on a number but halfway between two numbers. If the last two digits of the present "reading" of the register are 29, the "units" dial pointer will point to 9, and the "tens" dial pointer will be very near the "3" (just a little on the "2" side). (We see this clearly, in a slightly different situation, in Figure 14.)

That makes reading the register a bit tricky. Of course those who read meters regularly can get the full numerical reading of such a register at a glance.

6 OPERATION ON 120/240 V THREE-WIRE SINGLE PHASE AC CIRCUITS

6.1 Introduction

The work so far has been predicated on the use of our hypothetical watthour meter on a 120 V, single phase (two-wire) AC circuit, as that allowed me to delay (until now) some small complications.

But in fact the preponderance of electric service to residences and small businesses is on a 120/240 V single phase (three wire) basis, and so many watthour meters in fact are arranged to deal with that.

6.2 A simple adaptation

The meter mechanism I have described is easily extended to that situation. We see the basic concept in this figure:

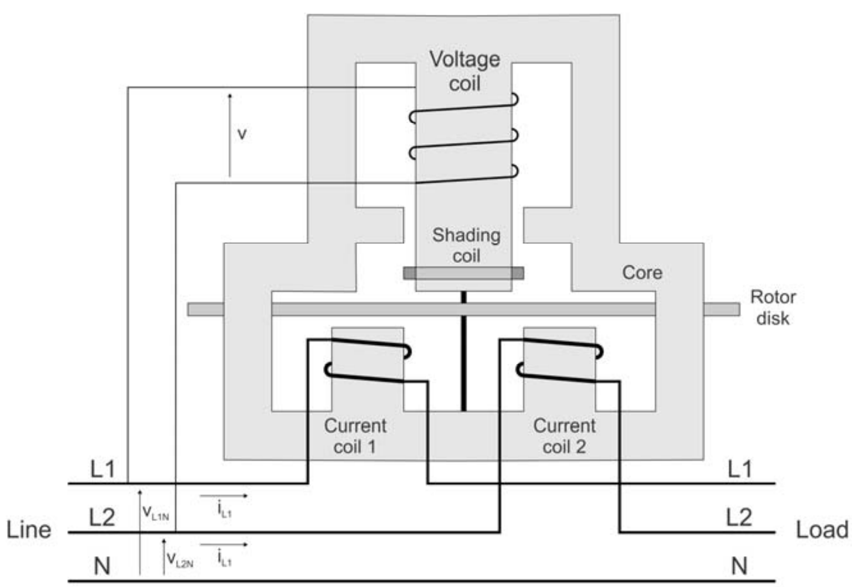

Figure 17. Application to 120/240 V circuit—conceptual

This type of AC power circuit is actually two two-wire 120 V circuits, with individual “hot” conductors, L1 and L2, but with the neutral conductor (N) common to both. The 120 V loads in the using premises are arbitrarily assigned to one “leg” of the other, and there is no assurance that the instantaneous magnitudes of the two currents are the same.

We note the instantaneous current in the two line conductors (which pertain to those two circuits), i_{L1} and i_{L2} [18]. We also note the instantaneous voltages which pertain to those two circuits, the voltage from L1 to N (V_{L1N}) and the voltage from L2 to N (V_{L2N}) [19]

Since (for our present purposes) the torque generated by the work of the left current coil has exactly the same effect in the rotor disk as the torque generated by the work of the right current coil, then the total instantaneous torque is thus proportional to the product of the voltage across the voltage coil (v) and the quantity (i_{L1}-i_{L2}). (The minus sign comes from the fact that the magnetic field from the right current coil interacts with eddy currents in the opposite direction as those from the left current coil.

As to the first circuit (conductors L1 and N), the instantaneous power is the product of V_{L1N} and i_{L1}. And as to the second circuit (conductors L2 and N), the instantaneous power is the product of V_{L2N} and i_{L2}.

The total instantaneous power is of course the sum of those two instantaneous powers.

But we do not have two separate processes multiplying V_{L1N} by i_{L1} and multiplying V_{L2N} by i_{L2} to produce two torques that we can add together.

The key to this conundrum is that conductors L1 and L2 are fed from the opposite ends of the secondary of the utility distribution transformer serving this customer (and likely several others). Conductor N is connected to the center of that winding.

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[18] Note that the two arrows for i_{L1} and i_{L2} point in the same directions. They indicate the sign conventions that will be used when mathematically referring to those currents. They do not suggest that, at a typical instant, the two currents are in the same direction. In fact they are at most instants in opposite directions (as the voltages on the two legs, V_{L1N} and V_{L2N}, are always of opposite polarity).

[19] Again these arrows show the mathematical sign conventions for these two voltages. They do not suggest that, at a typical instant, the two voltages are of the same polarity. In fact they are always of the opposite polarity,

Thus, **at all times**:

$$v_{L1N} = \frac{v}{2} \qquad (10)$$

and

$$v_{L2N} = -\frac{v}{2} \qquad (11)$$

So given that the voltage coil puts into the operation a flux proportional to v, we can also think of that as being proportional to both v_{L1N} and $-v_{L2N}$.

That being the case, it is appropriate that the overall (instantaneous) torque be proportional to the product of v and the quantity (i_{L1}-i_{L2}), which is just what the circuit of Figure 17 does.

6.3 A common actual implementation

Although I postulated above that the "left current coil" and "right current coil" aspects of the motor were essentially identical, in practice may factors can make that not exactly true.

To overcome any problems from this lack of symmetry, in practice a slightly more complicated implementation of a meter for use on 120/240 V circuits is often used. We see the principle here:

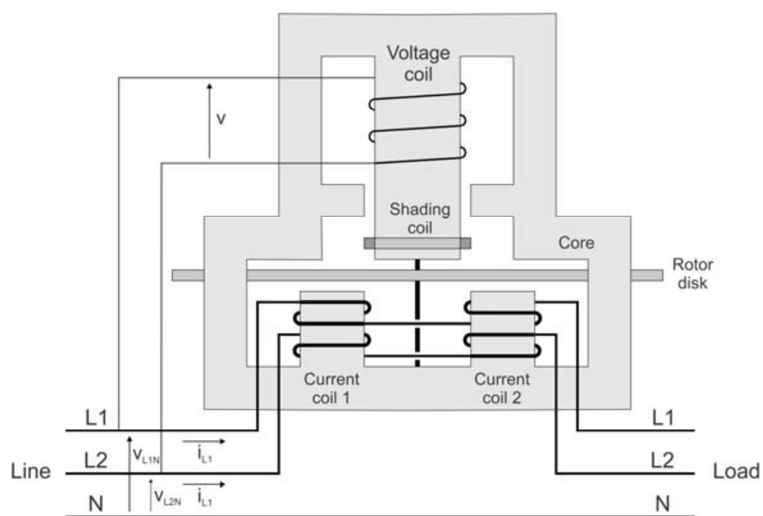

Figure 18. Application to 120/240 V circuit—better symmetry

The difference from the circuit of Figure 18 is that each of the two "hot" conductors, L1 and L2, goes through a winding on both the left and right current coils. But the whole thing works out the same way.

In fact, in many actual designs, the physical positions of the L1 and L2 windings are reversed on one of those two current coils, in order to even more closely attain perfect symmetry. We see that here:

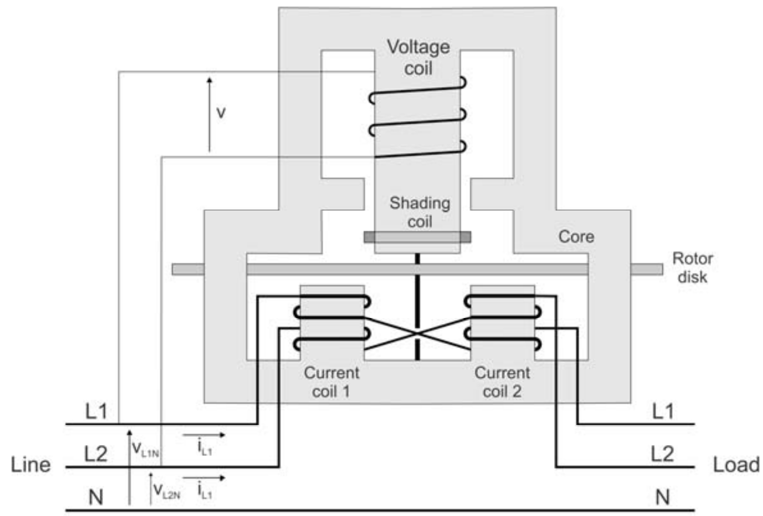

Figure 19. Application to 120/240 V circuit—better symmetry yet

7 ON THE OTHER HAND

The detailed explanation of the operation of the motor of an electrometrical watthour meter in section 4 involved these two concepts:

- The voltage coil causes a magnetic flux to flow through the rotor disk. The change in that flux creates voltages in the disk, which in turn lead to “eddy currents” in the disk.
- The current coils cause a magnetic field to be created through the disk. This interacts with the moving charges of the eddy current to produce a force on the disk, which constitutes torque on the disk.

What I slickly did not mention is:

- The “stream” of flux created by the voltage coil (itself a magnetic field in one sense of the term) is in fact a result of a magnetic field (in the other sense of the term) created by the coil.
- The magnetic field (in one sense of the term) generated by the voltage coil in fact causes a stream of flux, which is in fact a magnetic field (in the other sense of the term).

That having been realized, could we not equally as validly imagine the operation of the motor this way?

- The current coils cause a magnetic flux to flow through the rotor disk. The change in that flux creates voltages in the disk, which in turn lead to "eddy currents" in the disk.
- The voltage coil causes a magnetic field to be created through the disk. This interacts with the moving charges of the eddy current to produce a force on the disk, which constitutes torque on the disk.

Yes, we can.

In reality, both of these visions of the operation of the motor coexist, both leading to the same result (or perhaps, more accurately, collectively leading to the same result).

But this reality means that the mathematical analysis of motor operation is much more complicated than that reflected in my presentation here. And that is best left to true experts in that area!

8 THE METER "CONSTANTS"

8.1 Introduction

On figure 1, on the meter nameplate, we find two labeled numbers. **Kh**, with the value 7.2 (curious), and **Rr**, with value 13-8/9 (especially curious). The astute reader may notice that the product of these is precisely 100. But it turns out that this is just an accident of this particular meter configuration.

Both these values, in different ways, are constants that describe the relationship between the rotation of the rotor disk and the advance of the register reading.

The value **Kh** is simply the number of watt-hours (Wh) represented by one rotation of the *rotor disk*.

The value **Rr** (the register ratio) is the number of turns of the *pickup gear* of the register (see figure) that will cause a full revolution of the *units dial pointer* (that is, an advance of the register reading by 10 kWh).

8.2 The whole train

But as we try to relate these two values to the overall scheme, there is a missing link: the number of turns of the *rotor disk shaft* required to cause one revolution of the *pickup gear*. This is often called the *shaft reduction*, which I symbolize as **Rs**.

In typical meters, that ratio is 100 (but in some models 50, and in some 200). But sadly, its value almost never appears on the meter nameplate.

If we go through the algebra (which I will spare both of us), taking proper account of the various units involved in the definitions, we find out that, in any case:

$$Kh \bullet Rr = \frac{10{,}000}{Rs} \qquad (12)$$

We see this work out (exactly) in the example meter, where **Kh** is 7.2 (on the nameplate), **Rr** is 13-8/9 (on the nameplate), and **Rs** is 100 (that would be in the specification sheet for the meter, maybe). Therefore, **for this meter**, as we noticed earlier:

$$Kh \bullet Rr = 100 \qquad (13)$$

If for some reason we want to know the value of **Rs** for a given meter, we can get that from:

$$Rs = \frac{10{,}000}{Kh \bullet Rr} \qquad (14)$$

where we get **Kh** and **Rr** from the meter nameplate.

Note that the nameplate on the meter in Figure 1 is in two parts. We can think of the lower part as being associated with the motor and the upper part as being associated with the register (it is actually part of the register: the register "dials" are in fact printed on it).

We note the Kh is actually defined as a property of the motor, and thus it is fitting that it is stated on the lower part of the nameplate. And Rr is actually defined as a property of the register, and thus it is fitting that it is stated on the upper part of the nameplate (which is actually part of the register).

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