AC electric energy transfer experiment

Horacio Munguía Aguilar[1], Rigoberto Franco Maldonado[2], Luis Barba Navarro [3]
Departamento de Física, Universidad de Sonora, Hermosillo, Son. México 83000

E-mail: hmunguia@correo.fisica.uson.mx;

(Recibido el 20 de junio de 2018; aceptado el 29 de junio de 2018)

Resumen
Se muestra un experimento para ilustrar cómo la energía eléctrica de CA puede invertir su dirección de flujo. Esta es una situación que ocurre, por ejemplo, en los sistemas fotovoltaicos hogareños actuales en los que la energía producida se convierte en CA que puede usarse en la carga eléctrica doméstica o desviarse a la red eléctrica. Este experimento solo utiliza piezas y equipos de laboratorio comunes, así como un disco rotativo de inducción electromagnética fabricado como sensor de energía doméstico CA.

Palabras clave: Energía de CA, experimento de circuito, medidor de energía..

Abstract
An experiment for illustrating how AC electric energy can reverse its flow direction is shown. This is a situation that occurs, for example, in today home photovoltaic systems in which the energy produced is converted into AC which can be used up in the home electric load or diverted into the electrical grid. This experiment only uses common laboratory parts and equipment as well an electromagnetic induction rotary disk made as AC home energy sensor.

Keywords: AC energy, circuit experiment, energy meter.

PACS: 01.50.My, 01.50.Pa, 07.50.Ek **ISSN 1870-9095**

I. INTRODUÇTION

Beyond the electromagnetic explanation on electric energy and power transfer processes, about which there is enough information [1,2], electric energy transfer in direct current circuits are easy to comprehend and determine because we just need to know the current direction and the voltage polarity in the circuit element in order to determine if power is delivered or absorbed and with this, energy consumption is readily established. Unlike DC circuits, in AC circuits these processes are not very clear. Furthermore, there are no simple circuits which allow students to visualize this process. In the following paragraphs we are going to show an experiment that illustrates how AC electric energy can be transported between different elements inside an electric circuit.

A simple DC circuit is shown in figure 1 where two batteries in parallel power a load. If the batteries are equal with the same voltage level, currents I1 y I2 will be identical with a value of ½I3. If, for instance, the right battery had less charge than the left, its potential V2 will be less than V1 and the current I2 could be negative whereby the left battery will be charged by the right one. This means that left battery absorb power and the right battery deliver it. Of course, the internal batteries resistance will limit this transference. In general, for any circuit element with a V potential and a current I flowing in it, their associated power P=VI will have a sign which reveal if the power is absorbed or delivered. According to the passive sign convention [3] in the first case the sign will be positive and negative in the second.

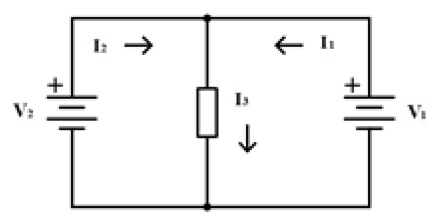


FIGURE 1. Two batteries in parallel sharing a load.

AC electric power and energy
A little more difficult to comprehend is the AC electric power and energy condition in AC power supplies. Figure 2 shows a similar circuit to the figure 1 but with AC power sources.

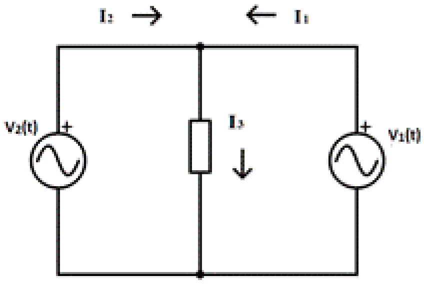


FIGURE 2. AC power supplies connected in parallel sharing a load. The current arrows are for reference.

The sources in this circuit cannot be considered as batteries as there are no AC batteries, but it is perfectly possible that an AC power supply absorbs or deliver electric power. In this case, we will suppose that both sources are sinusoidal with identical frequency but possibly with different phase and amplitude. Of course, these sources must have an internal resistance because if they do not have it (ideal sources) we would have an inconsistent circuit.

In order to understand this case, it must be remembered that the electric parameters in AC circuits (current, voltage, power) are handled in averages values [4]. A typical AC voltage source is a sinusoidal waveform:

$$v(t)=V_m \sin \omega t \quad (1)$$

In this, Vm is the amplitude in volts and ω the frequency in radians. When a load is applied to this source the resultant current is, in general:

$$i(t)=I_m \sin(\omega t+\theta) \quad (2)$$

Where Im is the amplitude in amperes and θ the phase in radians. The instantaneous power will be

$$p(t)=V_m I_m \sin \omega t \sin(\omega t+\theta) \quad (3)$$

And the average power

$$P=\frac{1}{T}\int_0^T p(t)dt=\frac{1}{2} V_m I_m \cos\theta \quad (4)$$

This means that the average power will be positive or negative depending on the phase angle between voltage and current. The term cosθ is known as Power Factor (PF) [3].

Power is delivered when $-\pi/2<\theta<\pi/2$ and is absorbed otherwise. For a capacitive element $\theta=\pi/2$ and the average power will be zero. For an inductive element $\theta=-\pi/2$ and also the average power is zero. For $\theta=0$ the power is delivered and reaches a maximum value. For $\theta=\pi$ the power is absorbed and also is maximum. Therefore, in order to reverse the power flow in an electric load we should change the phase θ from zero to π. This can be accomplished in different ways. In order to exemplify this we have built an experiment based on the circuit shown in figure 3. This is a circuit similar to the one in figure 2 but in this circuit the AC power supplies are represented by two identical step down transformer T1 and T2 (12 volts, 3 amperes). The outputs from the transformers are parallel connected taking care that their leads are in phase as indicated by the black points above the coils in the schematic. This can be verified with an oscilloscope. The load is a 12 volts lamp, the same voltage as the output from the secondary's transformers. Transformer T2 input is directly connected to the electric outlet and transformer T1 is driven by a variable transformer TV (Variac) which will allow us to change the input voltage to T1.

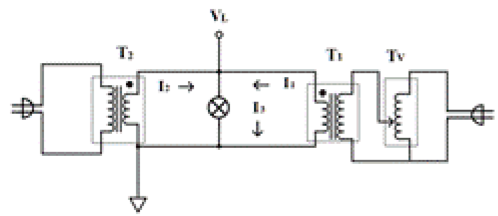


FIGURE 3. Two transformers in parallel powering a lamp.

Initially, Variac TV output voltage is adjusted to be equal that the standard grid voltage, in our case 127 volts. When the currents are measured with a digital multimeter, it is observed that I1=I2 and I1+I2=I3. Next, carefully increasing Variac TV output voltage, and so T1 input voltage, it will be noted that current I2 decreases while I1 and I3 increases. Accordingly, VL will also increase. As we continue increasing this voltage, there will come a time when I2 current becomes nearly zero. Additional increments in the Variac voltage will again increase I1 current. Care should be taken not to increases further this voltage up to the point of overheating the transformers. In our circuit 14 volts is a safe limit. See table 1.

TABLE 1. Currents variation as the voltage from T1 is increased.

V_L (volts)	I_2 (mA)	I_1 (mA)	I_3 (mA)
11.48	228	228	453
12.00	155	317	465
12.50	95	376	467
13.12	10	474	478
14.00	121	780	502

The most relevant fact in this experiment is the reduction in the current I2 to almost zero followed by a rise in this current. Another curious fact is the apparent failure to accomplish the Kirchhoff current law: I1+I2=I3.

Initially, the lamp current coming from T1 and T2 is received in equal parts. As the power from T1 increases, its current I1 offset I2 up to the point where this latter becomes zero. Additional increases in I1 drive I2 in the opposite direction, which is equivalent to an 1800 phase shift. But this shift cannot be appreciated in a common multimeter inasmuch as these only measure average values. One way to observe this current change would be through a low value resistor inserted in the secondary of T2 and using an oscilloscope in order to watch the I2 phase current by means of VI. See figures 4 and 5.

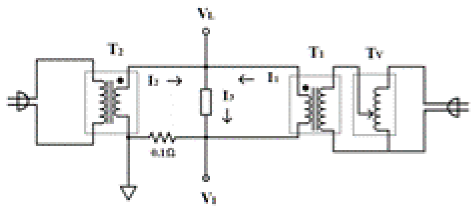
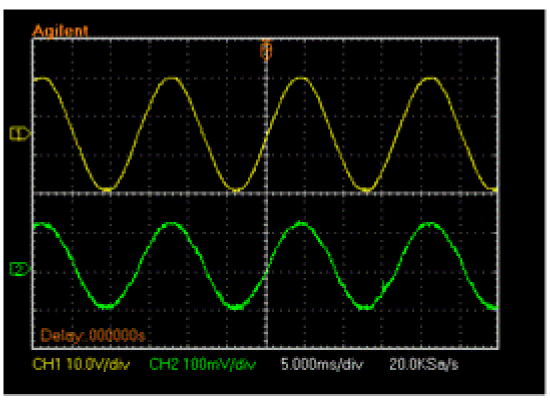


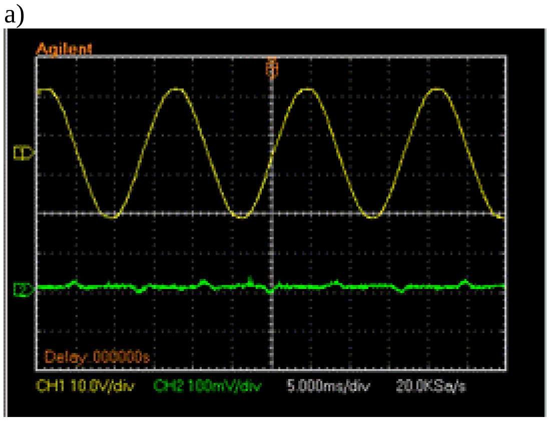
FIGURE 4. Inserting a low value resistor for I2 phase monitoring.

This phase inversion implies that transformer T2 is no longer delivering power to the load but instead absorbs it from T1. In fact, transformer T2 is returning energy to the mains through the household outlet. This is so because transformers are not a power supply but a power converter and voltage VL is the result of the superposition of the induced currents on the secondary's winding of transformers T1 and T2. Of course, the power in T2 is still equal to the product of VL and I2 magnitudes and the phase cosine between them that had just changed its sign.

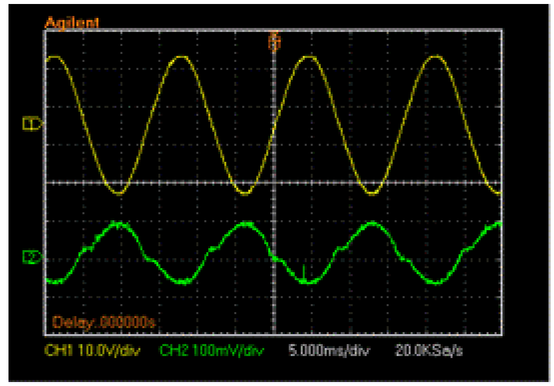
The reason for the apparent non-fulfillment of Kirchhoff current law is that this is applicable at every single moment, and the digital multimeter average several squared discrete measurements over certain time lapse, and with this mask out sign, distortion points and phase shift present in the signal measured.



a)



b)



c)

FIGURE 5. Phase inversion as seen in an oscilloscope at 0.1Ω resistor as input voltage in transformer T1 is increased. Top signal is VL and the bottom signal is VI. Figure b shows currents cancellations and figure c shows current inversion

Sensing electric energy flow direction. A more striking way to observe the change in the energy flow direction in AC current is by means of a traditional household electricity meter (watt-hour meter). This is an electromechanical apparatus which works on the principle of magnetic induction on a metallic disk [5]. See figure 6.

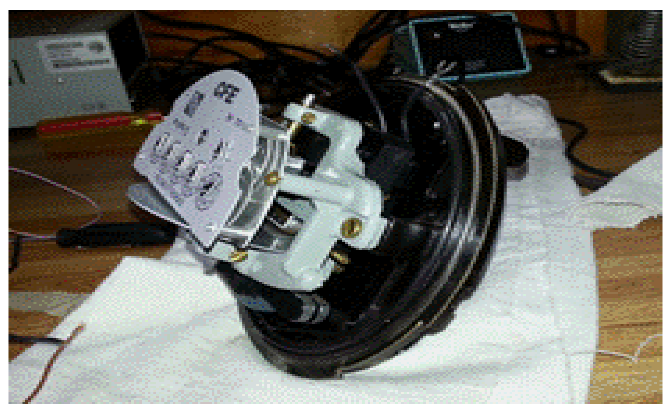


FIGURE 6. Traditional household electricity AC energy meter with its front cover removed.

This meter is formed by two coils embracing a disk near their upper and low face in order to induce eddy currents in the disk with which it interacts generating a rotational force. See figure 7. The upper coil, known as voltage coil, has a large inductance with many turns of thin wire over which is applied the line voltage. The lower coil, made with a few turns of thick wire and known as current coil, is series connected with the load whose current is going to be sensed. The rotational speed of the disk is proportional to the magnetic flow generated by both coils, i.e. to the power consumed. Their direction indicates the energy flow course: from or to the mains power (into the plug or out the plug). As the disk rotates, it moves a series of disk gears which, at the end, causes the rotation of the display needles whose position measure the energy transferred.

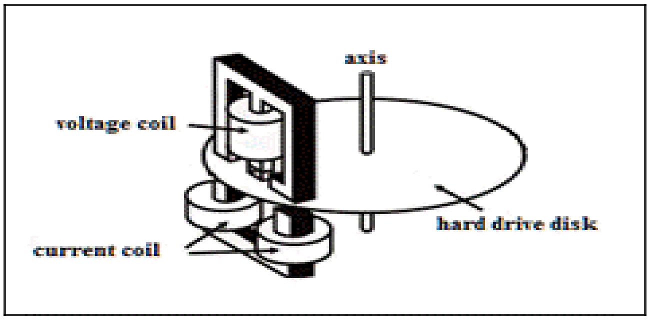


FIGURE 7. Electromagnetic induction disk meter outline.

It is not easy to get a brand meter and used it to observe the energy flow direction change, so we have built a homemade electromagnetic induction disk in order to observe this phenomenon in a qualitative way. For this, we have used the aluminum disk of a damage hard drive including its spindle which is a very low friction support for its axis. Mounted on an L-shaped structure the disk is embraced in one of its edges by the voltage and current coils as shown in figure 8. The coils used were extracted from a junk electromagnetic meter but different coils can be used, taking into account that the coils must have the aforementioned features. In any case it is always necessary to make some trial and error attempts.

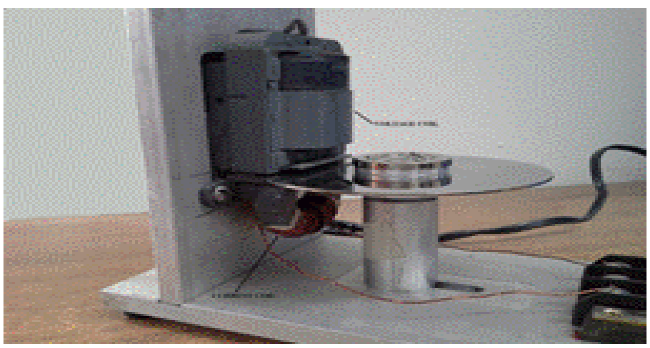


FIGURE 8. Homemade electromagnetic disk induction energy direction sensor.

The current coil is placed instead of the 0.1 Ω resistor with the purpose of sensing I2 curent. Repeating the transformers circuit experiment, it is clearly noted how the disk changes its rotation direction when the I2 phase changes by 1800, i.e. when the energy flow changes direction from the right transformer to the left transformer.

CONCLUSIONS

It has been shown a simple experiment that illustrates a technique in which the AC electric energy flow can be reversed. On this occasion, the energy is transferred from different points (electric plugs) within the same electric grid. In the case, for example, of a grid tied photovoltaic system the inverter circuit, which is where the DC energy is converted into AC energy, is also responsible of the energy injection to the electric grid. This is done in a similar way as in our experiment when we increased the input voltage in transformer T1 by means of the Variac. In a photovoltaic system this operation is accomplished by a smart inverter which takes care of the energy injection into the mains when certain conditions, like solar energy availability and voltage level, are fulfilled.

REFERENCIAS

[1] N. A. Morris N. A., Styer, D.F., *Visualizing Poynting vector energy flow in electric circuits*, Am. J. Phys. **80**, 552 (2012).
[2] I. Galili I., Goihbarg, E., *Energy transfer in electrical circuits: A qualitative account*, Am. J. Phys. **73**, 141 (2005).
[3] Fundamentals of Electric Circuits, Charles Alexander & Matheu Sadiku. McGraw-Hill Education, 5th Edition, pp.11-12 (2012).
[4] Average voltage tutorial, Retrieved (2017) from http://www.electronics-tutorials.ws/accircuits/average-voltage.html
[5] Kerry Megraw, *The Theories and Modeling of the Kilowatt-Hour Meter*, (2002). Retrived from: http://www.idc-online.com/control/The_Theories_and_Modeling_of_the_Kilowatt-Hour_Meter.pdf
[6] This is a fine video showing a kilowatt meter internal operation: https://www.youtube.com/watch?v=5SZDHgrysv8&t=1194s