WATTHOUR METERS

A watthour meter measures electric energy consumed by a utility customer in units of kilowatthours (kWh). The meter does this by measuring the integral of the active power with respect to time. This integral represents the energy delivered to the load (electric utility customer) in the interval over which the integration is done, and the units for convenience are in blocks of 1000 × W. The watthour is the electric energy used in 1 h when the average power during the hour is 1 W. The watt is the unit of active power and is defined as the rate of change of energy delivery to a load. The watt is the power used when a current of 1 A flows through a 1 Ω resistance.

The watthour meter has been called the cash register of the utility industry and certainly from the viewpoint of the customer it has served this one purpose very well for over 100 years (1). In essence, the watthour meter transforms customer dollars to utility dollars and thus has enabled electric utilities to bill relatively accurately for electric energy use and create (using revenue dollars earned) a multitrillion dollar transmission, distribution, and generation infrastructure worldwide.

The watthour meter measures active power, which represents the real power used by customers in end-use applications, such as heating, cooling, lighting, process control, electric machines, and running computers. Other components of energy at the power frequency level (fundamental 60 Hz to 50 Hz) include apparent and reactive powers. The measurement of these two quantities will not be addressed herein in detail, but certainly all three quantities form the basis of power network flow and define the electric product/service. For example, the reactive power, measured in kilovolt-amperes reactive (kVAR), controls primarily the voltage profile in power systems but does not contribute directly to end use. The apparent power *S* measured in kilovolt-amperes is all the power available to a customer, and from the ratio of active to apparent power, we may determine the power factor, which is an important factor in adjusting the reactive power. Certain types of watthour meters may measure all three quantities (active, reactive, and apparent) of power and many others such as harmonics.

Another purpose that the watthour meter is increasingly being used for is to provide both the utility and customer with information. The meter may provide not only revenue information, but also real-time demand, energy use patterns, profiling of loads and potential equipment failure information, and further control of equipment and other information technologies (Internet, cable) may be routed through the meter. The next generation of meters may well serve as the utility's information gateway to the customer.

THE DEVELOPMENT OF REVENUE METERING

With the invention of the electric light in 1879, Thomas Edison made the first electric equipment, the incandescent lamp. He knew that there was not only commercial value in lighting but also in heating homes and in transportation. Difficulties had to be overcome, especially because most people were unfamiliar with electrical technology and electricity, as well as its value compared to gas. Certainly to be of commercial value, electricity had to be measured. Edison was well aware that, in order to enjoy commercial success, he had to be able to deliver accurate measurements of electric use. The Mazda Light Company was first formed with Edison to solve the problem of accurate measurements in 1881 with the development of the chemical meter. With respect to a present-day meter, this was a primitive device. Basically, its operation hinged on the use of two electrodes. After a period of time, the electrodes in the chemical bath would interchange mass. Then the electrode would be weighed at the start and end of the billing period. This was also an attempt to make electricity more palatable to users in that the product (electricity) could be weighed much as one would weigh produce in the food market. This meter was used for a few years but became obsolete prior to the introduction of alternating current.

During and well after the time of the chemical meter, several leading people focused on satisfying customers by developing accurate metering. Among these people were Thompson, Shallenberger, Lamphier, and Duncan. The companies that these people worked for are still manufacturing watthour and other meters. Thompson was the founder of the Fort Wayne Meter Company that eventually became part of General Electric. The work of Lamphier became the genesis of Sangamo Electric Company (today known as Schlumbergee). Shallenberger was associated with Westinghouse (now ABB). Lastly, Duncan was the founder of the Duncan Meter Company (now Landis & Gyr).

The first practical wattmeter was developed by Professor Elihu Thompson in 1889. It was the first practical meter to measure true watthours and was awarded the 1889 Grand Prize at the Paris Exhibition. It could be used for alternating current (ac) or direct current (dc) electric power systems and became the industry standard. This was a significant advance over Edison's chemical meter, but it was not up to present-day standards. It is still remarkable for its innovation considering it was developed over 100 years ago. Also, in the same time period, Oliver Shallenberger developed an ampere-hour meter that was used exclusively in ac systems. This meter was adopted by many utilities because of low cost. However, with the increased use of ac, Thompson's meter was the desired choice because it measured watt-hours, which is the appropriate measure of electric energy.

The requirements of electric companies in the early days exceeded the availability of meters. Consequently, much electric energy was sold on a per-lamp cost basis. By 1890, it was recommended that this practice be halted and that in large metropolitan areas meters be used. This development in replacing the flat rate with a metered rate was made possible by the meters developed by Thompson and Shallenberger. The next several years witnessed the introduction of new meters by Duncan and Lamphier, which were primarily based on the pioneering work of Thompson and Shallenberger. In 1894, Shallenberger achieved one of the most important discoveries made in the metering field. He applied the induction meter, which would only previously measure ampere-hours, to measure watt-hours. He accomplished this via the method known as the lagging process, which continues to be at the crux of the metering field.

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

The first modern meter was introduced in early 1903 and is known as the Type 1 induction watthour meter. It was characterized by its compactness, high torque, ease of adjustment, large four-dial register, and long life. In 1913, the combination lag and light load plate was introduced. By 1925, F. Kinnard developed temperature-compensated magnets. Also, at this time, it was deemed necessary to respond to the rapidly increased use of electricity to form a mechanism for educating people in the utility industry on the proper maintenance and techniques associated with watthour meters. This organization was chartered with the University of Florida as the Southeastern Metermen's Association. This organization is still going strong and is now known as the Southeastern Electricity Metering Association (1). The middle 1920s saw a boom in the use of electricity and, as a result, saw the introduction of longer-range accuracy and increased current-carrying capacity in meters. Standardization of mounting dimensions was formed in 1934. In particular, the standardization of the "S" type meter and an agreement that manufacturers would produce two standard types of single-phase meters. One was the type "A," and the other was known as the type "S" meter. By 1938, the change to installing meters outdoors was the result of better materials being used in construction resulted in new problems. The main problem was in decalibration of the retarding magnets caused by current surges (due to switching and lightning) causing the meter to speed up. This problem was rectified by the introduction of harder magnets, which were able to better resist knockdown under surge conditions, such as Alnico II. By 1948, the General Electric Company introduced the I-50 meter, which had magnetic suspension. This eliminated the need for replacement of the expensive jewel bearings in meters and increased calibration stability. The continued growth of residential loads resulted in two further improvements, one in 1955 extended the meters range from 60 A to 100 A, and the other improvement in 1957 increased the range to 200 A. Today we see up to class 320 meters used for 400 A service and class 600 meters (bolt-in type) are available.

Up to the 1970s, the many improvements in metering were primarily the result of the dominant manufacturers. After this time, innovative new firms, such as Scientific Columbus, TransData, and Process Systems, among others, have produced novel breakthroughs in metering. The use of electronic and solid-state technologies has been on a steady increase. 1975 witnessed a major event in the introduction of the JEM-1 and solid-state watthour standard (SC-10) from Scientific Columbus. By 1982, the first commercially available solid-state register was produced. Today we see a revolution in the way meters may be applied to not only provide billing data but also to serve customers as an information gateway in energy use and communications.

MATHEMATICAL DEFINITIONS USED FOR THE MEASUREMENT OF POWER

The basic mathematical expressions recommended to be used in metering under single-phase sinusoidal conditions are given herein and are based on Ref. 2. In particular, it should be noted that Budeanu's theory is the approach most familiar to those in industry and the one taught in universities, and it is certainly the method most commonly used in instrumentation. Unfortunately, Budeanu's theory is not adequate for nonsinusoidal situations (3,4). Instead, the recommendations of IEEE Working Group on Nonsinusoidal Situations, chaired by A. E. Emanuel, should be used (2). Power theory under nonsinusoidal situations will not be developed herein; rather the sinusoidally valid approach used historically will be developed. Let us consider the single-phase case assuming a sinusoidal voltage and current.

For voltage, we have

$$v = \sqrt{2}V\sin(\omega t)$$

which, if applied to a linear load, will result in a current of the form

$$i = \sqrt{2}I\sin(\omega t - \theta)$$

where

I = root-mean-square (rms) value of current
V = rms value of voltage
$\omega = 2\pi f$
f = frequency in hertz
θ = phase angle

The instantaneous power in watts is

$$p = vi$$

p is composed of two components, an active and reactive component.

$$p = p_{\mathrm{a}} + p_{\mathrm{q}}$$

where

$$p_{\mathrm{a}} = VI\cos\theta[1 - \cos(2\omega t)] = P[1 - \cos(2\omega t)]$$

and

$$p_{\mathrm{q}} = VI\sin\theta\sin(2\omega t) = Q\sin(2\omega t)$$

The power p_{a}, which is an instantaneous quantity, is a result of the active current component, and represents the rate of change of energy

$$w_{\mathrm{a}} = \int p_{\mathrm{a}}\,dt = Pt - (p/2\omega)\sin(2\omega t)$$

w_{a} flows in one direction from the source to the load, and its rate of change is positive. On the other hand, the power p_{q} is a result of the reactive part of the current, and is the rate of change of energy

$$w_{\mathrm{q}} = \int p_{\mathrm{q}}\,dt = (Q/2\omega)[1 - \cos(2\omega t)]$$

w_{q} is an oscillatory quantity between the source and load and contributes no net energy to the load.

The active power in units of watts is

$$P = (1/kT)\int_{\tau} p\,dt = VI\cos\theta$$

where

$T = 1/f$, the cycle in seconds
k = an integer number
τ = the time when the measurement begins

The reactive power in units of vars is

$$Q = (\omega/kT)\int_{\tau} i\left[\int v\,dt\right]dt = VI\cos\theta$$

The quantity Q is the magnitude of the oscillating power p_q. With an inductive load, Q is positive, and with a capacitive load, Q is negative.

The apparent power in units of volt-amps is

$$S = VI = \sqrt{P^2 + Q^2}$$

In addition, the power factor, which is a unitless quantity, is

$$\mathrm{pf} = P/S$$

COMPONENT FEATURES AND OPERATING PRINCIPLES

Types of Meters

Watthour meters record energy and measure it in kilowatt-hours. The meters come in many types.

1. *Demand meters* record the demand and/or maximum demand and are used to ensure equitable charges to customers. Demand is the rate at which energy is consumed and is measured in kilowatts. The maximum demand is the greatest demand seen during a period of monthly billing. The demand interval is the period of time upon which the maximum demand is determined in the register and is usually taken over 1 min to 60 min intervals. Demand meters usually are three-phase and transformer rated for commercial loads, but they may also be self-contained. Two types of demand meters are (a) integrating demand meters and (b) thermal demand or lagged meters. The integrating demand meters record an average power during consecutive demand intervals. The watt-hour meter is the driver behind the register, which in turn rotates proportionally to the amount of watt-hours in the interval. This meter would show the maximum demand during a certain time period. On the other hand, the thermal demand meter has a pointer that changes in accordance with the temperature variation in its elements due to the current flow. Because the meter responds to temperature changes caused by current flow, it responds more slowly than a normal meter. The main difference between these two meters is with respect to the demand interval. One follows a heating response curve, and the other follows regular intervals. Both types of meters give comparable results with the exception of certain loads, which have large peaks during a short time period (in this case, the thermal meter would be slow to respond). On the other hand, thermal meters operate on a heating curve similar to equipment on the line and thus are preferred by some utilities. Many utilities also use fully solid-state meters with digital displays to measure demand.
2. *Electronic meters* are solid-state devices and have no moving parts. In these meters, the voltage and current waveforms are sampled at specified intervals and digitized. The signals are then processed using appropriate power definitions.
3. *Hybrid mechanical or hybrid electronic meters* may have a memory function and use electronic displays and have a mechanical rotor.
4. *Load profile meters* are an electronic or hybrid meter with an on-board memory so that the energy used for a certain time interval may be calculated and then downloaded to a computer for further analysis.
5. *Mechanical meters* are in large part used in residential applications and are primarily single-phase and self-contained.
6. *Primary meters* are put in service on the primary side of distribution transformers, usually 12 kV. In this case, the customer would own the transformer and its associated losses. Also, primary meters are used when a customer has multiple points of service and it may be best to use a single meter rather than several.
7. *Pulse meters* are either mechanical or electronic and are used mostly by customers with energy management systems. In this type of meter, a pulse is set to be equivalent to a certain number of watt-hours, and the number of pulses in an interval will be the same as the average demand in the interval. A solid-state data recorder may be used to store and collect the pulses and has the ability of storing data to be read by computer via phone lines or handheld devices.
8. *Secondary meters* are located on the customers or secondary side of distribution transformers. In this case, the utility owns the transformer.
9. *Self-contained meters* are designed so that all the loads current flows through the meter. Depending on the size of the load, a self-contained meter may either be (a) plain meter or (b) demand meter.
10. *Time-of-use meters* record and store energy and demands during on-peak, off-peak, and other times as needed.
11. *Transformer-rated meters* record a fraction of the energy going to the load. Meters are not capable of directly being used on voltages above 480 V and currents greater than 400 A. Potential transformers (PT) and Current transformers (CT) are used in conjunction with the meter so that the meter is capable of measuring large loads (5).

Meter Form Types

The classification of meters into basic form types is necessary for meter selection and to use it in the correct manner with respect of current circuits and external wires. Table 1 (see also ANSI C12.10) illustrates many of the form types.

Andre E. Blondel's theorem says that "If energy is supplied to any system of conductors through N wires, the total power (energy) in the system is given by the algebraic sum of readings of N wattmeters (watthour meters), so arranged that each of the N wires contains one current coil, the correspond-

Table 1. American National Standard for Watthour Meters: Basic Meter Form Types

Form	SC/TR	No. Stators	No. Current Circuits	No. External Wires
1s	sc	1	1	2
2s	sc	1	2	3
3s	tr	1	1	2
4s	tr	1	2	3
5s	tr	2	2	3 (or 4)
6s	tr	2	3	4 wye
7s	tr	2	3	4 wye
8s	tr	2	3	4 delta
9s	tr	3	3	4 wye
10s	tr	3	3	4 wye (alt)
11s	tr	3	3	4 delta
12s	sc	2	2	3
13s	sc	2	2	3 (or 4)
14s	sc	2	3	4 wye
15s	sc	2	3	4 delta
16s	sc	3	3	4 wye
17s	sc	3	3	4 delta
35s	tr	2	2	3
45s	tr	2	2	3 (or 4)
1a	sc	1	1	2
2a	sc	1	2	3
3a	tr	1	1	2
4a	tr	1	2	3
5a	tr	2	2	3 (or 4)
6a	tr	2	3	4 wye
8a	tr	2	3	4 delta
9a	tr	3	3	4 wye

Note: tr = transformer rated, sc = self-contained, s = socket base, a = bottom connected.

ing potential coil being connected between that wire and some common point. If the common point is on one of the N wires (ground may also be included in N), the measurement may be made using $N - 1$ wattmeters (watthour meters)" (1). What this means is that energy may be metered using one less current and potential element than the wires in the system. Hence, we would use three stator meters for a three-phase four-wire system. Four kinds of watt-hour meters used in the United States typically apply to Blondel's theorem; these are forms 5, 9, 12, and 16. However, design modifications resulting from economics are also typically used by utilities. These include, for example, the $2\frac{1}{2}$ stator forms 6, 8, 14, and 15. The accuracy of these compromised design forms is contingent upon keeping the phase displacement between line voltages fixed. Figure 1 shows a simplified example of using a form 16s meter in a three-phase four-wire application.

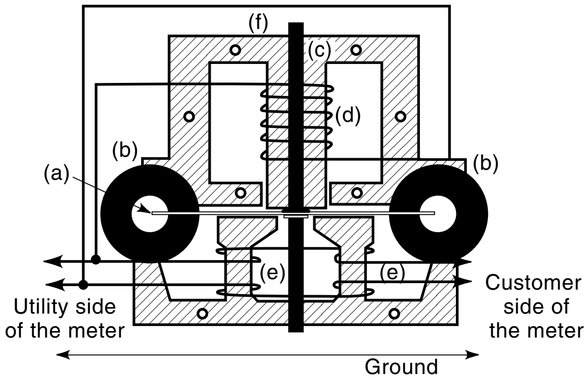

Figure 2. Main Components of a single-phase, three-wire, mechanical induction watt-hour meter. (a) Rotating disk; (b) braking magnets; (c) stator frame; (d) voltage coil; (e) current coils; (f) shaft.

Meter Components and Operation

A single-phase mechanical (induction) watt-hour meter is in essence a small induction motor that is used to measure kilowatt-hours. Figure 2 illustrates a three-wire single-phase induction watthour meter. The induction disk rotates because of the torque developed by the magnetic field generated by currents flowing through the meter elements. The stator (stationary frame), which becomes an electromagnet when energized, has two coils. The coil in series with the line produces a magnetic field in proportion to the line current. The other coil, which is connected across the line, produces a magnetic field proportional to the voltage. Because the two coils are on the same stator frame, they develop a magnetic field that produces a torque on the disk which is proportional to the load power. Further, there exists a permanent magnetic field developed by the braking magnets; it creates a damping torque in proportion to the disks speed. The rate the disk turns now becomes proportional to the measured power. The number of revolutions during a specified time period is indica-

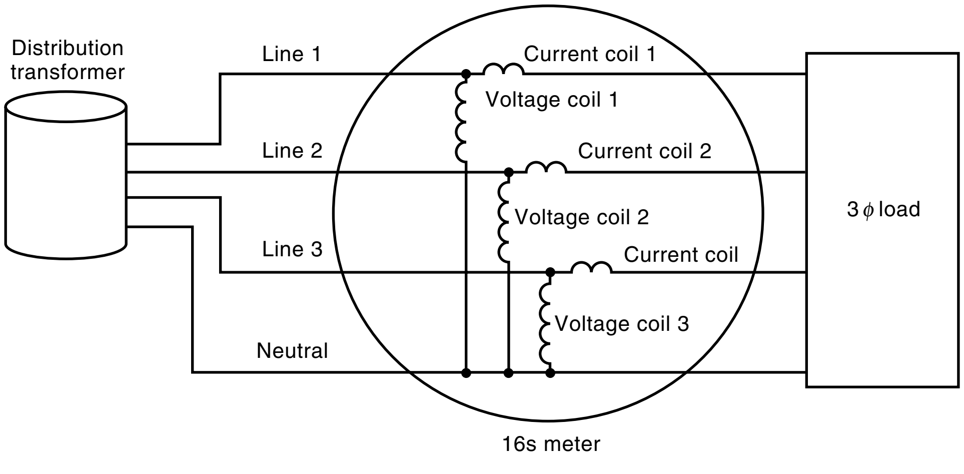

Figure 1. Connection of a form 16s polyphase watthour meter in a three-phase four-wire power distribution system. (Courtesy of RJC Associates/CTGI, Southeastern Electricity Metering Association Course 140 Class Notes, 1996)

Figure 3. State-of-the-art solid-state polyphase revenue meter—the ABB Alpha meter. (ABB Power T&D Company, Electric Metering Systems, Raleigh, NC)

tive of the power, and the power may now be displayed on the register through appropriate gearing between the register and the disk. A revolution made by the disk represents the watthours and is specified by the meters Kh factor, where Kh = (rated current × rated voltage)/(rotations per minute/60).

The main components of the induction watt-hour meter consist of (a) base/cover, (b) disk and spindle, (c) damping magnet, (d) electromagnet or stator, and (e) register. The cover is usually constructed of glass or plastic and is sealed to protect the meter from the elements and tampering. The disk is constructed of aluminum, fitting between the magnetic poles of the current and potential coils, and is mounted on a shaft. Eddy currents on the disk, induced by the potential and current coils magnetic fields, in turn produce a flux that interacts with the two coils that then cause the disk to rotate. The disk drives two elements: (a) the gears and dial pointers by which the revolutions are added to kilowatts of energy used and (b) the shafting and gears in combination with a timing motor that add the revolutions in each demand interval to determine the kilowatt demand. The damping magnet produces a braking force on the disk, which is placed between the poles of the magnet, so that the speed of the disk becomes proportional to the power used by the load. The stator serves to direct the magnetic fields developed by the current and potential coils. The register is constructed of dials that record the amount of energy. The dials are driven by the rotation of the disk through a set of gears.

Metering is made more attractive if the register is electronic. Electronic demand registers were made possible with the introduction of nonvolatile memory. Mechanical registers use an externally operated recorder and translator to do rolling demand calculations. Electronic registers can determine rolling demand internally. The main part of an electronic register is a microprocessor. If an electronic register is used with a mechanical meter, the disk rotation is typically sensed by optical devices. These optical sensors create pulses for each rotation of the disk or by detection of disk shaft motion. Hence, a pulse represents some energy used. The electronic register may perform tasks to establish time intervals, count and sum pulses for display information, and count and sum pulses for demand intervals.

A state-of-the-art solid-state meter, typical of those produced by leading manufacturers, is shown in Fig. 3. In general, solid-state meters give tremendous flexibility by providing sound economic benefits and useful diagnostic information. The ABB Alpha meter is an integral meter and register. With this meter, it is possible to gather, process, and store energy use and demand information on a four rate time-of-use (TOU) or demand basis. The TOU and demand data can be shown in watthours and either apparent energy (VAh) or reactive energy (VARh). The basic design, as shown in Fig. 4 with the components indicated, is compact. The chassis assembly houses the base, current and voltage blades, connecting cables to the circuit board, and lightning arrestor. The electronic housing contains the meter and register electronics on a single circuit board. The circuit board includes the voltage range power supply and dividing resistors. The housing also includes the LCD, nameplate, and battery. The circuit board can also be provided with (optional) relaying outputs. The cover provides for visual metering and an optical port and demand reset. Further, with a wide voltage range capability, it becomes possible to reduce the need (and reduce inventory requirements) for the many form types shown in Table 1. The Alpha meter can meter both form 8s and 9s transformer-rated applications, and the self-contained version can meter form 14s, 15s, and 16s applications. Of the 18 typical types of mechanical meters used today, the solid-state meter shown in Fig. 3 consolidates the form number down to five—reducing inventories up to 50%.

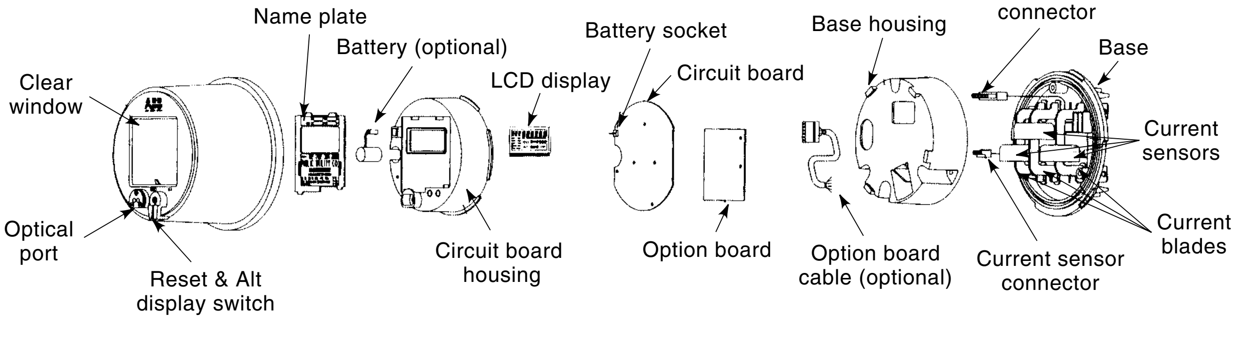

Figure 4. Main components of a solid-state polyphase revenue meter. (ABB Power T&D Company, Electric Metering Systems, Raleigh, NC)

THE FUTURE OF METERING

The future of revenue metering may be considered to be on our doorstep in that many of the components are here today but remain to be integrated into an acceptable system and developed with additional capabilities. For example, the ABB PowerPlus Alpha meter is capable of multiple functions, in addition to serving as a watt-hour meter, such as: voltmeter, ammeter, distortion indicator, power quality monitor, VAR meter, watt meter, phase rotation indicator, VA meter, phase angle meter, and circuit wiring checker. This increase in functionality opens many new applications branches up for the utility. The Alpha meter may be used for diagnostic testing, which involves determining the validity of the electrical service. The meter may be used as a power quality monitor. Such capabilities allow monitoring of voltage and current total harmonic distortion, time stamping of power quality disturbances, and recognition of momentary voltage sags. With regard to revenue metering, these meters record energy and demand values for both real and reactive, and real and apparent quantities. Further, load profile and event logs are available. The communications features included on the main circuit board allow for automatic meter reading and control. Depending on the pass code authority, the users (utility and customer) may access billing records, power quality events, and energy use and load profile information remotely via a telecommunications system to a personal computer. The telecommunications system may be telephone modem, radio, power line carrier, cable, or even satellite.

What the development of new telecommunications and metering infrastructure means is that it will become possible to market new services. This is of vital concern to utilities as competition and deregulation unfold. The telephone modem interfaces, with each meter being able to hold multiple encrypted passwords, will permit direct customer use metered data and support credit card dialing so that billing can be done to appropriate accounts. Further, the meters can also be programmed to follow a certain call in schedule, or call automatically if there are errors occurring. Several novel areas of future application are discussed in the following material. All these areas of meter applications are actively being studied by researchers and manufacturers.

Automation of the Home or the Smart House Concept

Revenue meters, such as the Alpha meter, which are designed for compatibility with protocols to access wide and local area networks like CEBus, permit great flexibility in load control. This then permits information to be transferred to home heating, ventilating, and air conditioning (HVAC) controllers and receivers. These elements then function as relays to the customers appliances. An entire new opportunity for sharing information with many home electronics-based devices ranging from pool pumps to televisions becomes possible.

Real Time Pricing

The utilities via the interactive network can communicate directly with home (and industry) electric systems. The customer would determine criteria for energy usage, and the utility would then via the telecommunications network download real-time pricing for the customer-specified energy usage. With a system such as this in place, it becomes possible to price-control appliances automatically to a customer's desired comfort and economic specifications.

Automatic Meter Reading

Automatic meter reading (AMR) technologies have been in existence for several years. The AMR techniques have typically been done by means of radio or power line carrier schemes. Novel methods under study now include the use of low earth-orbiting satellites. Two-way communication to meters in remote locations worldwide becomes feasible with the addition of communication elements installed in the meter. In general, the major manufacturers are intending to support several communications systems to enhance the application use of AMR. The main driving force behind AMR is the cost (when compared to standard ways of reading meters) and the need for having several items metered, monitored, and controlled. With the advent of retail and wholesale wheeling in a compet-

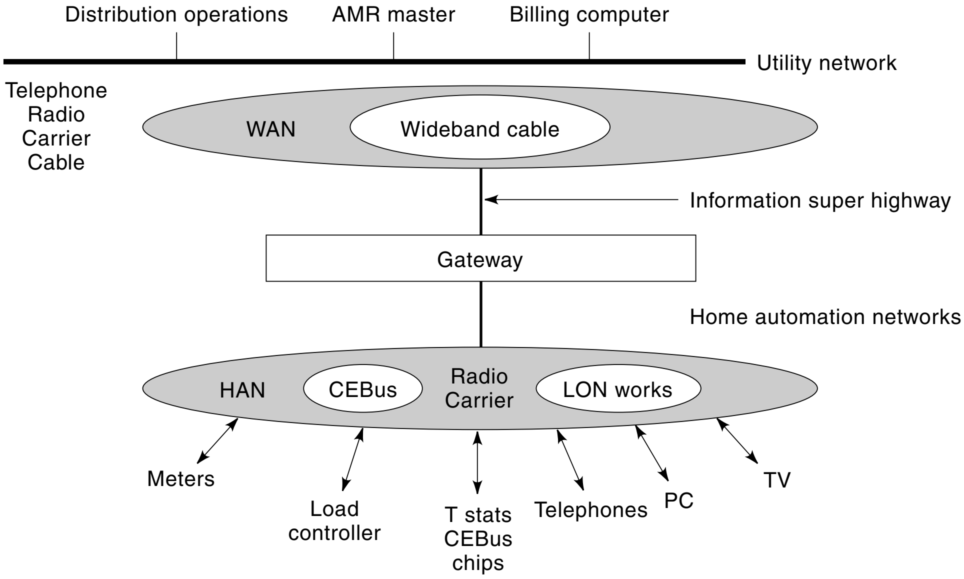

Figure 5. Automatic meter reading, billing, and control/service provision to most electrical devices and communications via cable and the information super highway. Other communication gateways possible are telephone modems, radio, power line carrier, and low earth-orbiting satellites. (ABB Power T&D Company, Electric Metering Systems, Raleigh, NC)

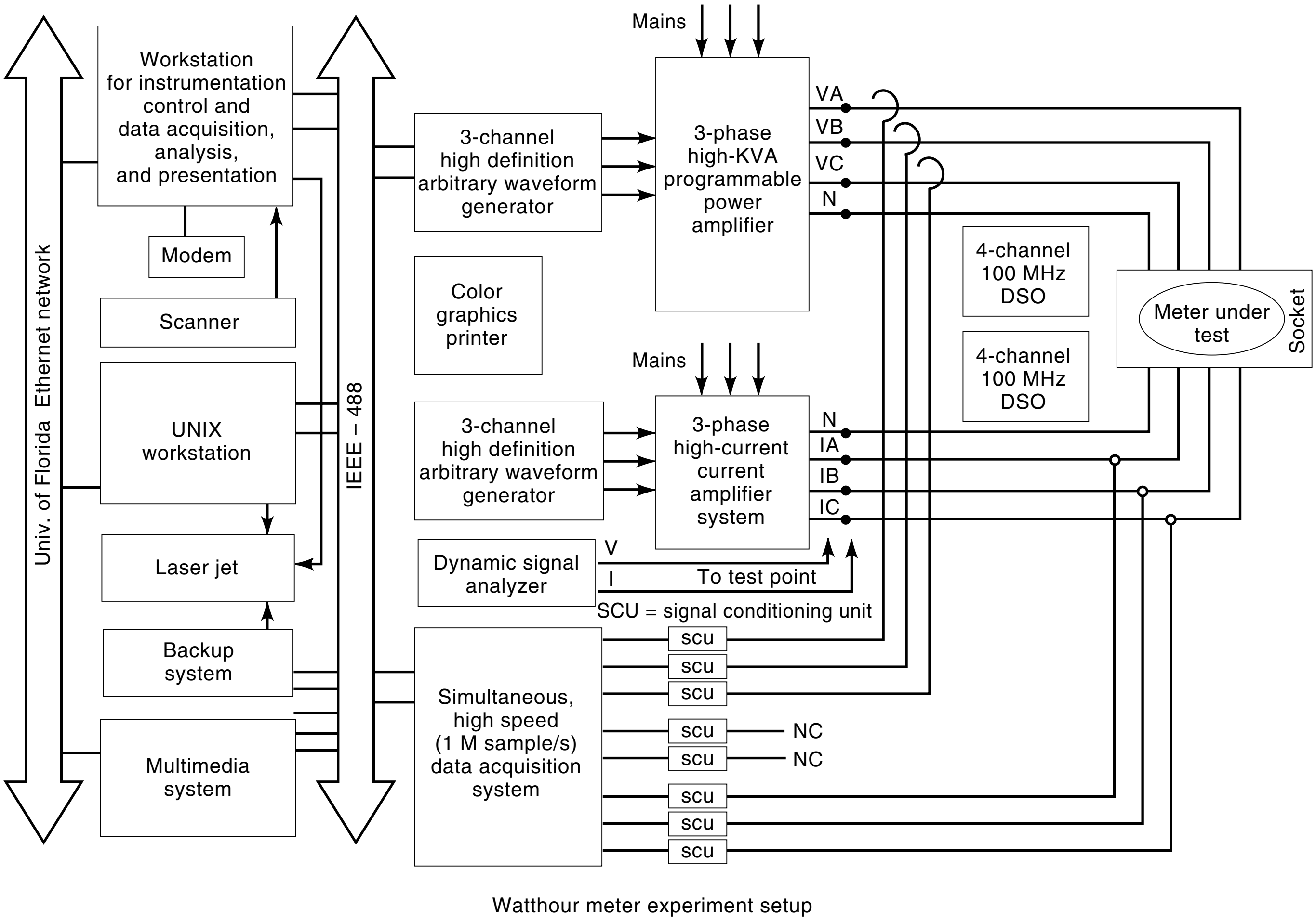

Figure 6. Watthour meter experimental setup for testing the meters performance under nonsinusoidal and unbalanced voltage and current waveform conditions. The unique test system at the Power Quality Lab at the University of Florida is capable of producing real-world arbitrary polyphase and synchronized voltage and current waveforms to apply to meters (and other power equipment such as relays, transformers, lighting, motors, and drives) under test to determine, for example, percent registration errors.

itive electric utility environment, AMR becomes more of a necessity than an option.

Challenges in Metering

We have come full circle from the early days of metering, described at the start of this article, in that a new product is being offered. From the past to the present, the product has been electricity. We must look beyond electricity metering to combined service offerings of such items as television, energy management or load control of appliances, security, and computing. Figure 5 illustrates this concept. The communications gateway using AMR may be telephone, radio, power line carrier, cable (as illustrated), or satellite. The challenges in making this complex system work are great not only because there are hundreds of millions of customers potentially involved but also because of the limitations of communications bandwidth, measurement technology, and conflicting standards. For example, it may be implied from Fig. 5 that an explosive growth in the use of electrotechnologies is expected to occur. In large part, these electrotechnologies are power electronics based. Power electronics (PE) are incorporated in such elements as variable speed motor drives (used in HVAC and many other applications), PCs, high-efficiency lighting ballasts, process controls, and a full range of appliances. The proliferation of PE-based devices means a consequent increase of power system harmonic and transient current and voltage waveform distortions and unbalance (6). Metering designed for 60/50 Hz operation may have errors under these conditions and this topic is addressed in the next section herein (7). There is a need to determine correct power definitions for nonsinusoidal and unbalanced conditions (3,4,8). Also there is a need to quantify properly and allocate equitably such costs as may be caused by these distortions so as to maintain a good level of power quality. In fact, it is noted in IEEE P1459 that “there is not yet available a generalized power theory that can provide a simultaneous common base for: energy billing, evaluation of electric power quality, and help in detecting the major sources of waveform distortion.” (2).

Calibration and Testing of Watt-Hour Meters. The term *calibration* is understood in the metering industry to define a process whereby the accuracy of the meter is adjusted. The term *testing* is used to define a process by which the accuracy of the meter is determined. Calibration is conducted carefully by each utility company, and results are traceable to the National Institute of Science and Technology. The traceability is accomplished by having the utilities transfer standard meters annually compared to known standards at NIST. Then the meters may be adjusted after a correction factor is determined using a watt-hour transfer standard in the utility meter departments primary measuring instrument, such as a Knopp model ST-31 automatic watthour meter testing system. Historically there have been two methods of calibrating polyphase meters: (a) series–parallel (single-phase) and (b) true polyphase. It has been considered to be acceptable for polyphase watt-hour meters to be adjusted using series–parallel calibration. However, in evaluating electromechanical watthour meters in Refs. 9 and 10 it has been found that under full load, three-element meters tend to run more quickly if used in polyphase loads than in series–parallel condition. On the other hand, two-element meters tend to run slow in polyphase load conditions when compared to series–parallel conditions. It should be noted that NIST standards and calibration are done for sinusoidal situations and that this does not necessarily apply very well to nonsinusoidal and unbalanced voltage and current conditions (11–13). These nonsinusoidal situations are becoming more prevalent as was previously discussed.

The testing of watt-hour meters, as well as many other power elements, under nonsinusoidal situations may be accomplished with a test system as shown in Fig. 6. Voltage and current waveforms generated mathematically or through field measurements may be downloaded to the computers on the left-hand side of the figure. These computers then digitize the waveforms and send them through the IEEE-488 (GPIB) network to arbitrary waveform generators (one for current and one for voltage). Power amplifiers then boost the analog signals to high power levels so that they may be applied to the meter under test. The readings of the meter under test are compared with a high-speed data acquisition system that is calibrated for each harmonic measurement. The data acquisition system then feeds the signals to computers for analysis and modeling purposes. Results for testing several typical watt-hour meters discussed herein are shown in Table 2. These results are for various voltage and current unbalances and total harmonic distortions. Further results may be found in Ref. 7. Directions for research indicated by these results include development of meter technologies appropriate to nonsinusoidal situations, development and use of appropriate power definitions to process nonsinusoidal, and unbalanced waveforms when computing watt-hours.

Table 2. Three-Phase Watthour Meter Percent Registration Errors[a]

	Office Building		Pump Station	
	Magnitude (rms)	THD (%)	Magnitude (rms)	THD (%)
Volts-phase A	122.52	2.96	125.40	3.78
Volts-phase B	123.44	2.68	115.83	2.66
Volts-phase C	121.41	2.09	115.20	2.12
% Unbalance	0.85	18.8	5.55	32.5
Current-A	4.75	4.66	3.39	96.90
Current-B	4.72	4.51	5.03	104.2
Current-C	4.58	2.94	5.71	83.88
% Unbalance	2.21	27.0	28.0	11.7

Meters Tested	Office Building Registration Error (%)	Pump Station Registration Error (%)
Hybrid meter 1	−5.57	−8.75
Digital meter 2	−4.76	−10.09
Solid-state meter 3	−4.37	−9.54
Solid-state meter 4	−3.04	−7.27
Digital meter 5	−0.94	+0.52
TDM meter 6	−0.19	−2.26
Electronic meter 7	−0.18	−3.24
TDM meter 8	−0.13	−2.56
TDM meter 9	−0.04	−0.70

[a] The meters were tested when subjected to unbalanced and nonsinusoidal voltage and current waveforms from a pump station (2 up to 150 hp adjustable speed driven pumps) and a typical office building (168,000 ft^2 with a 980 kW demand with a usual mix of lighting, personal computers, copy machines, and other office equipment loads).

Unbundled Power Quality Services: Revenue Metering Implications. Some utilities are expecting to be able to provide various levels of power quality services to customers. One type of service may provide "premium quality" or "UPS" grade power to a customer, and another may provide low grade power at a lesser cost to the customer. In this situation, it becomes important for the utility to be able to have the metering technology available to meter appropriately and bill the load under nonsinusoidal situations (12). The pressing business and research challenge is to design meters and develop definitions of power and billing schemes that are correct for various grades of electric services (13–16).

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