The Digital Revolution in Measurements

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Abstract-- **This paper considers what it means to make a measurement, and the changes in measurement technology over the years. The impact of the latest changes, which have resulted in most electrical measurements being done digitally, is explored. It is argued that the process of measurement can be considered equivalent to one of data compression. The smart grid will certainly result in many more signals being made available, and therefore a great deal of data compression will be taking place. Measurements will be made in parts of the power system presently unmonitored, as well as parts that are already well covered by instrumentation. The smart grid engineer must decide what it means to have "useful" information. Unless care is taken, the signal processing may furnish information that is not useful, and may not even make sense. The paper concludes by examining the possibilities of data compression from multiple separate signals.**

Index Terms—**Measurements, digital measurements, abstraction, data compression, measurand definition**

I. INTRODUCTION

IN THE 1880s, physicists were trying to "determine" electrical quantities such as the ampere and the ohm, based on definitions originating in the centimeter-gram-second system, itself not yet completely adopted for scientific use. These definitions led to apparatus that occupied a considerable amount of time and energy to set up and to use. (For example, the ohm was defined in terms of the resistance of a column of mercury of specified dimensions, rather than the resistance of a piece of wire.[1] This was considered a "fundamental" measurement because it involved the quantities length, mass and time, which were considered fundamental.)

It is hard to imagine now, but most of the scientists of the day came to believe that any measurement method that did not require heroic effort must necessarily be inferior. The very meaning of "measurement" was under discussion. (Could something be real that was not measurable? Was everything measurable necessarily real?) The orthodox view was that the measurement of electrical quantities ought to involve skill and exertion, and should use complicated and time-consuming apparatus. But there were a few who disagreed.

In fact, there were two fundamentally different aspects to the measurement process. One type of measurement was the *comparison* of the unknown with a standard of the same type. The various bridge circuits exemplify this type of measurement. The other type of measurement was the *observation* and recording of the quantity being measured. This was where the disagreements lay.

Building on work that showed how an electrical quantity could be made to have a physical manifestation, some fairly convenient instruments were developed that we might even recognize today. The developers were engineers, splitting away from physics.

By the late 1880s, Professors William Ayrton and John Perry in London not only had developed convenient instruments, but had gone so far as to label the scales of their instruments directly in volts and amps. The *direct-reading* instrument had arrived. Now, for the first time, it was possible to put an instrument into a circuit and get a reading in a matter of moments.[2]

Direct reading instruments represented a paradigm shift, a revolution in measurements. While bridges and the like were (and are) still useful for calibrating in a laboratory, "fundamental" measurements were largely abandoned in favor of more convenient direct reading instruments. For over a hundred years since their introduction, we have been following this path when we make a reading of an electrical parameter.

The result has been that during the last century, electrical engineering has gone on to provide instrumentation of greater and greater accuracy and wider and wider applicability. The century since Ayton and Perry has seen more rapid measurements, and more accurate measurements, and engineering in general has benefitted from all those improvements.

This paper presents the argument that there is now underway a revolution in measurements just as profound as the one of Ayrton and Perry and their contemporaries. This time it is the world of digital measurements that is at issue. Without digital measurements, there would be no smart grid. The case is made that digital measurements may not always give the expected results.

II. DIGITAL MEASUREMENTS

The measurement of power and energy has been of interest to electrical engineers since the beginning. Energy has usually been the basis of the electricity bill in the power

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business, for example, and the measurement of power is intimately involved in the operation of the system that delivers it. Over the years, many ways to measure power have been developed.

An electrodynamic measurement depends on the creation of two fields that interact. One field is caused by the voltage, of course, and the other by the current. The fields may be magnetic or electrostatic, though the magnetic form is the more familiar to most of us, as in Figure 1.

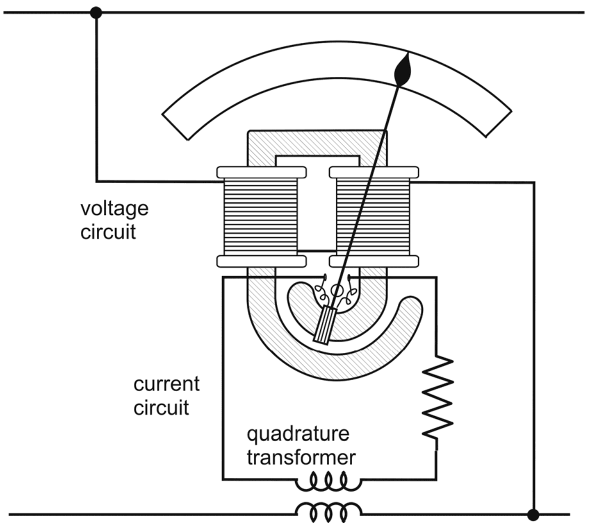

Fig 1. Sumpner Wattmeter

In this instrument, a "background field" is produced by the voltage coil, and the deflection is produced by the interaction of that field with the field of the current coil. The mass of the moving parts limits the speed of response, and the inductance and capacitance of the coils limit the frequency of input that can be measured accurately. It would be a good instrument that achieved a response accurate at 1 kHz, or an uncertainty better than 1%.

Back in the mid-1970s, a Japanese company called Yokogawa made a new – digital – wattmeter. Figure 2 is adapted from a block diagram of the latest offering from the company, a three-phase version.

The device has three voltage inputs and three current inputs. It accepts a current input and converts it into a voltage, and a voltage is simply buffered. Thereafter, an A/D converter converts each input into a digital data stream.

From the digitized signals, a value is computed for the power. There is nothing unusual about this, but when Yokogawa sent an instrument to the National Bureau of Standards (as NIST was then called), the rumor spread that the Yokogawa instrument was claiming a level of uncertainty that was beyond the ability of NBS to measure. In other words, the instrument was more accurate than anything NBS had available at the time!

That situation was remedied forthwith by NBS, of course, if it was ever true.

Most of us did not recognize it at the time, but what had happened was that the era of digital measurements had truly been ushered in. In the next section, we will examine what that means, and why it was a paradigm shift.

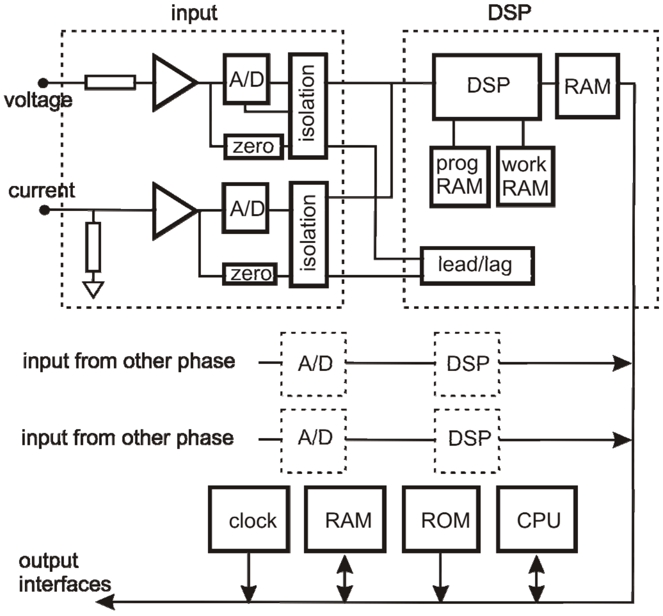

Fig 2. Yokogawa wattmeter block diagram

III. PARADIGM SHIFT II: IN PROGRESS

What had happened when the Yokogawa meter was developed was that the way of making a measurement had once again fundamentally changed. (The Yokogawa instrument may not have been the first time this kind of measurement had taken place, but I refer to it because it was the first that came to my attention.) In essence, the measurement was divided into three parts, the transduction from primary quantities, the conversion to digital, and the processing of the digital information.

These days, one can contemplate the use of 24-bit A/D converters. These give measurement results that are equivalent to uncertainties of a few ppm, about the same as a calibration in a national metrology laboratory. One can use some kind of long time constant filtering to reduce the effect of Type A uncertainties. Combining methods such as this, good measurements are readily made. Nowadays, most electrical quantities can be measured by digital equipment.

The thing that most of us in the profession are (apparently) not grasping (or perhaps not fully grasping) is that the digital solution offers *arbitrary* bandwidth, and *arbitrary* dynamic range, and – more importantly – it is capable of implementing any *equation*. Anything that is *definable* can be measured using digital processing of the signal.

The problem is this. It is perfectly possible to define things that make no sense, and then to implement the solution digitally.

The digital method should be forcing us to do something we have not always done, or done thoroughly. Since we can implement any programmed solution, whether it makes sense or not, we must think about the *meaning* of measurement. It seems we are not always up to the task.

Whatever we define, the digital method can implement it. It does not matter if the old methods relied on the quantity being measured to have limited bandwidth, or limited dynamic range: the new method can deliver a solution, provided the user can define the equation. Consider power as an example. Power is nicely defined by an IEEE Standard (1459-2010). And yet . . . .

There are loose ends. That this is a matter of some importance is shown by the report of a situation in Canada in which the digital electric meter of a large consumer was replaced by a different digital meter [3]. Before the replacement, the customer had a power factor of 0.95. After the replacement, the power factor was 0.88, as a consequence of which a penalty added to the bill. Since the customer load had not changed, the customer was somewhat perplexed and annoyed. The power company investigated.

They found that the two meters had used different ways of calculating the power factor. The "power factor" did not have two values (how could it?), but it had been calculated in two different ways. Both ways were technically correct on the assumption of sinusoidal values, and both had been certified correct by Measurement Canada.[1] However, the harmonic content of the load resulted in the two calculations not giving the same result.

The paper indicates that one meter measured Q by evaluating $Q = \Sigma V_h I_h \sin\theta_{h,}$ that is, evaluating the harmonic terms separately and summing them, and hence $S = \sqrt{(P^2 + Q^2)}$, whereas the other meter calculated $S = VI$ (that is, the rms quantities were directly multiplied). In both cases the power factor was then found using $\mathrm{PF} = P/S$. It is thus possible to find two different values for the power factor, each based on accepted calculation methods.

Another way of thinking about the problem is to ponder the definition of reactive power, often thought of as similar in some ways to real power. (After all, one can write the equations as the volts times the amps times either the sine or the cosine of the angle between them.) What is the definition of reactive power? As is happens, there is more than one definition. A recent study for NEMA (the National Electrical Manufacturers Association) found at least ten definitions being used in VAr-hour measurements [4]. While the various methods give the same solution if the waveforms are sinusoidal, the results differ if the waveforms are distorted. What that must mean is that they cannot all be "right."

How is the user to choose? These differences are more than a matter of having a different frequency response or a different dynamic range, they are fundamentally different definitions implemented by software. How can the same thing have more than one definition?

Obviously, the same *thing* cannot have more than one definition. The *things* defined by these various algorithms may have been given the same name, however. What that implies, in a general case, is that the user must decide what the measurement is *for*, and must examine the definitions to see if one is better suited than another.

Power factor is important because the power company may increase the electric bill to compensate them for the increased losses in delivering the power. Here the increased loss is not directly measurable, but the power factor is a surrogate. A "good" definition would thus be one that reasonably tracked the cost of losses.

In general, user choice in such matters seems a troubling concept. A better solution for this kind of situation is for there to be a single agreed-to and sanctioned definition.

Consider as another example the measurement of frequency for the power system. Frequency is an output from a device called a synchrophasor or a phasor measurement unit (PMU). PMUs are designed to comply with the requirements of IEEE Std C37.118.1, the 2011 version of which is an update of earlier standards. There are two problems. First, the very concept of phase is based on an assumption that the parameters being measured are sinusoidal and stationary, neither of which is applicable to the useful measurement of power systems for some applications. Second, the standard *defines* the frequency as something based on estimating the phase of the signal under consideration.[2]

Since phase is also a quantity that PMUs are designed to measure, the method seems obvious and simple, and often it works well. However, the method as defined is susceptible to noise, and the signal is noisy. We need to re-think the whole measurement, beginning with the definition and only then considering the implementation.

The need imposed by the digital method for us to think through the definition issue harks back to the century-old debate about the *meaning* of measurement. It is stressed in the Guide to the Expression of Uncertainty in Measurement (GUM)[3] that *a common source of uncertainty in measurements is failure to adequately define the measurand*. It is worth exploring that point.

The process of making a measurement involves several steps that can be usefully separated. The first step is the process of *abstraction.* Hermann Kopetz of the Technical University of Vienna, discussing fault-tolerant system design, wrote that *systems must be explainable by models of a complexity that can be handled by the human mind* [5]. In metrology, that means that what we get when we perform a measurement is an abstraction that can be understood. Once we have made the choice of abstraction, we can call the quantity we want to measure the *measurand.*

Having done that, we must decide on what we will use as the signal that allows us to evaluate the measurand. In the case of the voltage on a power system, there is often a transformer between the quantity to be measured and the device doing the measuring. The measuring device "sees" something called the *realized quantity.* It is part of the

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[1] Measurement Canada is responsible in Canada for ensuring the accuracy of measurements. They evaluate and certify measurement instruments.

[2] These remarks should not be considered as the views of an outsider finding fault with the group that wrote the 2011 Standard. The author of this paper was a member of the group.

[3] Available in English and French from BIPM at http://www.bipm.org/en/publications/guides/gum.html, accessed July 2012

process of making a measurement to make sure that the realized quantity is a good stand-in for the measurand.

If the measurand is energy, the stuff that an electricity bill is based on, it is possible to write a definition that does not include the contribution of harmonics. The utility generator was designed to produce power-frequency sine waves, and that is the commodity that the utility offers for sale. Suppose that we implement a method that calculates only the power-frequency component of the power, and generates a bill for that. Fine, you might say, nothing wrong with that.

But suppose there is a particular load that is rich in harmonics, and is actually causing a large harmonic current in the power system. If we were to include that current in the definition, and therefore in the measurement, the bill might be different. Should we not take that into account?

It is really our choice. Digital technology allows a new definition of what it means to make a measurement.

IV. MEASUREMENT DEFINED

Kelvin, Ayrton, Sumpner and the other early electrical metrologists struggled at a philosophical level to define what measurement is. In the 21st century, we can see that the act of measurement has two parts: extracting information from the world, and expressing it in some short and useful form. Our technology, in particular our digital methods and their vocabulary, allow us to define the first part of the process of measurement as *data compression*.

That may be considered heretical by some of our metrologist colleagues, but it is fair. This business of comparing something with a quantum-effect standard is the second part of the process, the *expressing* part of the measurement. But really, all we are doing when we make a measurement is extracting information from a signal and making it available for some particular purpose.

An alternating signal, such as the voltage on a power system is not "understandable" in the sense that Kopetz had in mind. Therefore, we engineers make an abstraction and say that the signal can be characterized by a relatively small number of (abstract) parameters. Typically, one of those parameters captures something of the *size* of the signal, another something of how rapidly it is alternating, and another something of how it is fixed with respect to a clock. There is no single way to do these abstractions. We could choose to use the peak amplitude or the average amplitude of half the wave, but we more often use the rms value because it has some convenient properties.

This measuring device then performs some form of data compression. The measurement of rms voltage, for example, could be by means of a hot wire or it could be a digital calculation. In either case the input (the realized quantity) is compressed to a single number that is the output of the process. These days, that number is expressed in terms of a multiple of a standard quantity, along with information that describes the confidence level that the realized value is within some range.

We have not always had the luxury of absolute standards based on quantum effects. (I do not refer here to the habit in some newspapers of measuring areas in football fields, and pressures in the number of elephants standing on the top of a Buick.) Back at the end of the 19th century, Friedrich Paschen was investigating the breakdown of gases subject to electrical stress. He was a careful and patient scientist, and his results were good enough to allow him to remark on what seemed like a seasonal variation in his results [6].

His equipment was not very good, however, and although these days we attribute to Paschen the existence of a minimum in the curve of withstand voltage against a pressure-distance product, he discovered no minimum. (That was discovered later by a worker with better pumps.) Further, Paschen did not even measure the voltage! However, his instrument reading did furnish a value that was related in some way to voltage, and for his purposes, that was enough. His name went into the history books.

It is so easy nowadays to measure things that are expressed in terms of standard units that we have lost sight of the fact that those standard units, those bases of comparison, are needed only for such things as commerce and engineering. In these fields, comparisons across borders, or across technologies, are central to trade or to progress. But a statement to the effect that sulfur hexafluoride is 2.5 times stronger than nitrogen when it comes to electrical breakdown requires no external reference. Of course, the statement is most useful only when qualified in terms of the range of variables involved, and such a description is best expressed in familiar units. Comparison with standard quantities may not be essential, but it adds immeasurably to the value of the measurement.

V. FREQUENCY MEASUREMENT

If we accept that the central act of measurement is no more than data compression, we can see that there is nothing in the process that requires us to restrict the algorithms to considering only the information that is *in the signal itself.* The well-known MP3 method of data compression, for example, is built around an understanding of the way the human auditory system processes sound, and that information is surely not incorporated in the sound signal itself.

How might smart-grid technology benefit from this way of looking at measurement? The possibilities are endless, and so I single out the PMU for consideration. Let us consider first the measurement of frequency.

The consideration starts by examining the abstraction "frequency." What is that, exactly? When one asks one's colleagues, one gets a similar reaction to the invitation to describe a spiral staircase without using the hands. Then "It's the number of cycles in a second." No, it isn't. We do not have a whole second to make the measurement in a PMU. Cycles per second is simply the unit in which we express the result of the measurement, just as miles per hour is a unit of speed.

Specifically, frequency is written as the rate of change of phase, but that only works in a system in which all the parameters are stationary, which makes the measurement somewhat pointless. If we accept that something "nearly stationary" can be defined well enough for use, then rate of change of phase will work for frequency so long as phase can be defined. In a PMU, phase is measured by comparing the realized quantity with a synthetic waveform that is defined and can be calculated with arbitrarily small uncertainty. It follows that phase can be found if the third unknown in the description of a phasor – the amplitude – can be found with small enough uncertainty.

And so long as there are no harmonics in the waveform.

In fact, it seems to me likely that, since a PMU is expected to furnish a value for the three unknowns of a phasor in something close to one cycle, the best that can be hoped for is a statement that has rather low confidence levels. When the signal starts to show a change, it is very difficult to know whether the amplitude is constant right away, and almost impossible to know in a short time whether the frequency or the phase is changing.

I can imagine a situation in which a changing input to a PMU is reported with a level of confidence that improves as subsequent data are analyzed. If the user is prepared to wait, a better level of confidence may be available.

Such a process would be equivalent to reporting at time $t = t_1$ one value for the result of a measurement of the signal at time $t = t_0$, and at time $t = t_2$ updating both the value and the confidence level. We can suppose such a method can be implemented using digital signal processing methods.

A further step may result from the prior knowledge that the frequency prior to the moment of interest is quite nicely calculable, and the physical knowledge that an instantaneous frequency jump is not possible in a power system.[4]

But that is not the end of it for the PMU. The notion of the PMU is based on the usefulness of information that is time-synchronized (by GPS) and that can be expressed as a phasor at power frequency. To accomplish this feat, the PMU samples the incoming signal from all three phases of the power system, and from that data stream it calculates the equivalent positive sequence phasor values: amplitude, phase angle and frequency.

PMUs have so far been designed to serve the needs of the power system analysts and operators. They are also providers of information for protective relaying systems. But it need not stop there. The sampled signal from a PMU that is close to a generator could be used to inform generator operators about unbalance in the machine conditions, or about harmonics that could cause heating (and hence shorter insulation life). A PMU that was further from a generator could provide information on the local power quality. All that would be needed for these applications to become real would be to program the "PMU" with algorithms to do the appropriate calculations.

VI. A PMU-BASED "MULTIMETER"

It is not just PMUs that can benefit from the new capabilities. Recall the situation of a harmonic-rich load that we considered earlier. We said that the bill might change if the harmonic power was included. It is perfectly possible to imagine that the energy bill could be adjusted by the direction that harmonic energy was moving. A load that *removed* harmonic power might see a *decrease* in the bill when harmonics were included, whereas a user that was inserting harmonic energy would pay for the privilege.

If you can imagine it, they can program it.

We should recall that electricity bills are based on energy use only as a matter of convenience: there is nothing fundamental or "scientific" about that method of billing. Edison started it as a way to recover his costs and make a profit from the electric company that he had invented. The price of energy had to be set high enough to recover his capital costs in addition to his operating costs. He could have structured his charges to include a separate charge for capital costs, but he did not. We have followed suit ever since. And we have made several instruments that can measure that energy.

The information that is needed for the data compression that gives us the energy value is available in a PMU: the time, the voltage and the current. In fact, considerable investment has been made in making this information available: there are VTs and CTs and GPS clocks.

We can, in fact, make all sorts of measurements with this information. A sort of high-power multimeter is possible, as shown in Figure 3.

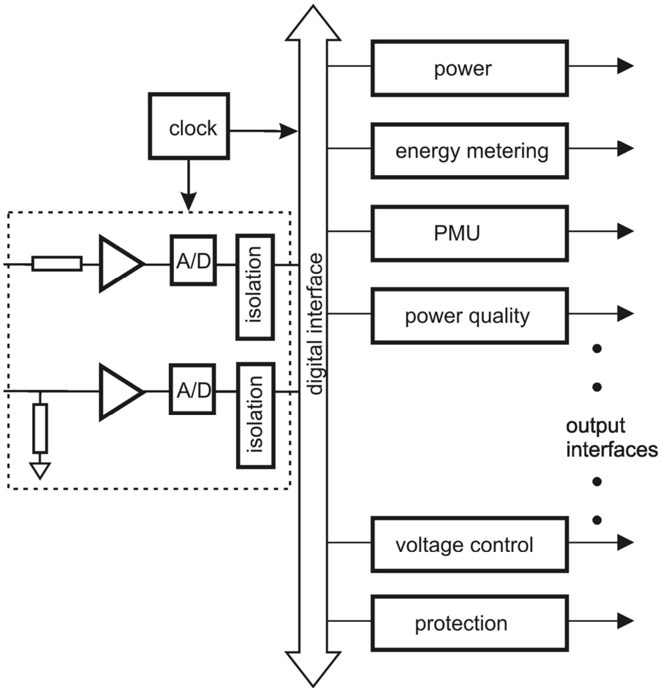

Fig 3. Multi-purpose "meter" block diagram

As Figure 3 shows, once the instrumentation transformers are installed, and the A/D process taken care of, we can do the data compression to make available readings of power (for control systems), energy (for billing), phasor data (for

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[4] At least, the frequency cannot jump instantaneously using any "ordinary" meaning of the word frequency. In fact, as a representative of the speed of rotation of the generators, the frequency can change only quite slowly. However, the phase and the amplitude of the voltages and currents can change from one cycle to the next if there are faults or switching in the system. Such changes may then appear to be steps, as they occur on a time scale comparable to the time window of the sampling process in the PMU.

operator use), power quality, voltage control, and even protection. It may be necessary to do some correction in software for the artifacts of the instrumentation transformers (which may be better suited to some applications than others) but the technology exists to make this possible.

VII. CONCLUSIONS

The second revolution in measurements has brought us full circle. We are obliged to consider again what it means to make a measurement. The results obtained with the measurement of reactive power enable us to say with certainty that anything that can be defined can be measured: but we still cannot say that anything that can be measured is necessarily real.

Realness is not the most important factor in measurements. Usefulness is. We are now at a point in the evolution of metrology that we are required to be very careful about defining the quantities we measure, and to consider how those definitions may be implemented. The algorithms that are implemented in a measurement may be fast and efficient, but that will not guarantee that we are getting useful information.

Whether the harmonic contribution to a power measurement is appropriate or not is a matter of application. Whether frequency is measured by Fourier transform or phase difference will change its meaning. Our technology gives us the freedom to choose, and we should choose carefully.

We may generalize: The smart grid is a grid characterized by rapid control of multiple distributed parameters, connected and made workable by a network of digital measurements and communications. We must get into the habit of considering carefully how we go about obtaining values of the things we measure.

VIII. ACKNOWLEDGMENT

The author gratefully acknowledges the conversation with Jerry Stenbakken of NIST that got him thinking about these matters.

IX. REFERENCES

[1] The original source material describing the work of the British Association and others is contained in documents from the middle to the late 1800s, for example the *Philosophical Magazine* and the *British Association Reports* for many of those years. More accessible descriptions of the work going on during this period exist. The story of the wire *vs* mercury column standard is told by Forest K. Harris in *Electrical Measurements*, Wiley and Sons, New York, 1952 in Chapter 2. More detail may be found in *The Values of Precision*, edited by M. Norton Wise, Princeton University Press, Princeton, NJ, 1995, and in particular, Chapter 6 of that book, and in *The Morals of Measurement*, by Graeme J.N. Gooday, Cambridge University Press, 2010, and in particular Chapter 3 of that book.

[2] In 1873 Ayrton taught in Japan the first-ever university electrical engineering classes, see "William Edward Ayrton at the Imperial College of Engineering in Tokyo . . ." by Yuzo Takahashi, IEEE Transactions on Education, Vol 33, No 2, May 1990, pp 198-205. There he met John Perry. They returned to England in 1881 to teach at the Finsbury Technical College, and to develop electrical measurements, see *A Social History of Engineering* by W.H.G. Armytage, Faber and Faber, London, 1961. Their work had can fairly be said to have caused a lasting separation of electrical metrology and physics in the presentation of a paper at the Physical Society: *Students' Simple Apparatus for Determining the Mechanical Equivalent of Heat*, W.E. Ayrton and H.C. Haycraft, Proc. Phys Soc, London, Vol 12 P. 295, 1894, available at http://iopscience.iop.org/1478-7814/13/1/329 accessed Nov 2012.

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X. BIOGRAPHY

Harold Kirkham received the BSc degree and the MSc degree from the University of Aston, Birmingham, U.K. He received the PhD degree from Drexel University, Philadelphia, PA.

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In 2009 he left JPL and moved to the Pacific Northwest National Laboratory, to pursue work on sustainable energy and the smart grid.

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