On a Singular Apparent Energy Definition for Metering and Tariffs

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Synopsis

The article gives the need for a singular definition for apparent energy (unit VAh). Multiple definitions has been a cause for confusion and poor implementation of apparent energy metering and tariffs. Apparent energy measurement can play a vital role particularly in the developing countries which is facing a crisis of high losses and low degree of utilization (high degree of blocking) of generation, transmission and distribution equipment due to highly inductive loads, loads injecting harmonics, and switching loads.

We show how the apparent energy based tariff is the only single parameter based tariff that is fair and incorporates an embedded power factor based discount mechanism. By having a singular definition of apparent energy and simple digital signal processing based metering technologies we can effectively trigger an electrical revolution - where the market will see rapid sales of efficient electrical appliances. It is a Win-Win solution where the consumers can avail tariff discounts by becoming more efficient while the electric utilities can increase its revenue considerably both through loss reduction and through the collection of penal charges from the defaulting consumers. The revolution will see a change in the labeling of appliances with its rating indicated in terms of VA and consumption in VAh.

1. INTRODUCTION

Readers would recall that between 1996 to 2002, a number of publications on Apparent Energy metering and tariffs had been published by our R&D Centre. This coupled with efforts in educating the regulatory and governing bodies, has yielded some results. Over the past few years, a handful of utilities particularly in northern India, such as Delhi, UttarPradesh, and Himachal Pradesh, have taken the bold initiative to meter and bill directly on the basis of the unit of Apparent Energy, namely kVAh. On its web page[1], South Asia Forum for Infrastructure Regulation (SAFIR), has put in focus, the Uttar Pradesh Electric Regulatory Commission (UPERC), for the best practices followed by it, particularly, the introduction of kVAh billing for high voltage consumers and for loads above 50 kW in non-domestic LMV2 and institutions' LMV4 categories in 2001-02.

However, in our opinion, the implementation of the kVAh metering and tariffs has been carried out in a non-systematic manner, resulting in only partial results. While it was originally intended for use in the LT sector, which does not have a PF based tariff, it has wrongly replaced the already well planned multi-part HT tariff in Uttar Pradesh. The Delhi Electricity Regulatory Commission (DERC) in its tariff schedule for the year 2006-07 for the Non-Domestic LT (NDLT1) Category has charged 487 paise per kVAh instead of 535 paise per kWh. This means that the consumer would be paying more under the new tariff if his/her PF is less than 0.91. The kVAh tariff was therefore considered one that penalizes the consumers.

It is, therefore, not surprising, that there has also been a lot of hue and cry about inflated bills in a few parts of our country [2] due to installation of electronic meters that record apparent energy. Also, a number of technical articles in conference proceedings and journals that has categorized upto six different definitions for Apparent Energy [3] has added to the confusion already created. The electric utilities already in a dilemma had to take the heat off from the politicians, were therefore, desperately seeking guidance and direction on this new tariff unit.

During this period, due to restructuring activities, the activities of our centre had become dormant.. In the current year, we have embarked on re-starting the operations of our centre with an aim to refocus on the challenging task of kVAh implementation and to correct the mistakes that the utilities and tariff regulatory bodies have been committing.

This paper marks the beginning of a series of articles to be published in continuation to the ones that have appeared earlier in Electrical India. Here, in the sections that follow, we re-iterate the basis for defining Apparent Energy. Also, how digital signal processing techniques enable us to design meters that can compute Apparent Energy in the desired manner.

2. HISTORY ON METERING

In the nineties, there was a period when the static energy meters would mimic the functions of their electromechanical counterparts. In [4], an algorithm for computing kVAh from kWh and kVArh pulse inputs is described.

In the same period, we recall how the CBIP Specifications for A.C. Electrical Energy Meters [5], had caused a great deal of confusion on what should be the appropriate technique for kVAh measurement. This is because in [5], in the section "Guidelines for Combined kWh, kVArh, kVAh Measurements" (Clause Nos. 3.5.4 and 4.6.1)" p. 39, there are a number of statements which had defined kVAh in an inappropriate manner. In [6], we have explained why the CBIP Technical report no. 88 needs correction.

About a century earlier, in April 1888, Shallenberger designed the AC Ampere-hour (Ah) meter and marketed over 120,000 meters over the next 10 years. These 'Shallenberger (Ah) meters' were very popular. It was the first metering technology that could effectively measure electrical energy and also a precursor to the Apparent Energy meters that we are promoting today. Similarly, the 'Ah' tariff was the first successful tariff structure applied on an electrical network.

The only technology that preceded the Shallenberger meters was the primitive clock meter that was patented by Samuel Gardiner in 1872. Since the tariff was based on a single parameter, namely, the number of hours of load operation, the power consumed by the load was irrelevant.

3. DEFINING A NEW METERING PARAMETER

From history, we can observe that whenever a new parameter is defined, it is done in the most direct and straightforward manner and should have a strong basis. Also, a new parameter is defined only if it makes sense. More importantly there has to be a purpose or a need has to be felt in our daily lives.

We also observe that simplicity in technology or operating principle has been a major influence, particularly in electrical energy measurements. The Shallenberger Ah meter and later the Ferraris kWh meters ruled over a century simply because of the simple operating principle behind these instruments.

3.1 Need to Define Apparent Energy

In our case, the purpose of defining Apparent Energy is to use it for tariff purposes. A tariff system should be designed with the following objectives.

1. Consumers pays for the total cost of energy, namely capital cost, running cost, and maintenance cost of energy generation, transmission and distribution system (including the losses).
2. Consumer pays for his own consumption and not for the neighbours' consumption, and,
3. Consumer is motivated to improve the power system efficiency and reduce losses.

We have described in [7], why the present active energy (kWh) tariff is unfair and does not meet any of the three primary objective. Beside the above three primary objectives that a tariff is expected to meet, there are secondary objectives which, when met, would enable easy realization of the tariff system. The secondary objectives are,

- The tariff should be simple and easy to implement.
- The equipment (meters) necessary to implement the tariff should be simple and inexpensive.

The apparent energy tariff and the meters to support this tariff meet all the above requirements.

If we plot a graph of the cost of energy vs. power factor, keeping voltage, V, and current, I, constant, we get a gently drooping curve as shown by Curve A in Figure 1 (see [7]for details). An appropriate tariff structure would be one which closely follows this curve. From the figure, we observe that, the revenue collection using the characteristic curve of active energy (kWh) would be highly unfair particularly to the efficient consumers operating at high power factors who are paying considerably higher.

The need to define Apparent Energy as a tariff parameter is felt because, the nature of the load has changed considerably over the past two decades. The utilities have very little control over the nature of the load, as the choice is vested with the consumer. Moreover, in a system, where market is flooded with a wide range of inefficient appliances and products, there is an urgent need felt to systematically weed out these inefficient products from the market.

By the term 'inefficient', we are in particular referring to three types of loads - (a) Highly Inductive Loads, (b) Loads that inject Harmonics, and (c) Switching Loads. Such loads are responsible for high line (technical) losses in our distribution system and low degree of utilization (blocking) of the distribution infrastructure (switchgear, cables, lines) (see [8] for more details).

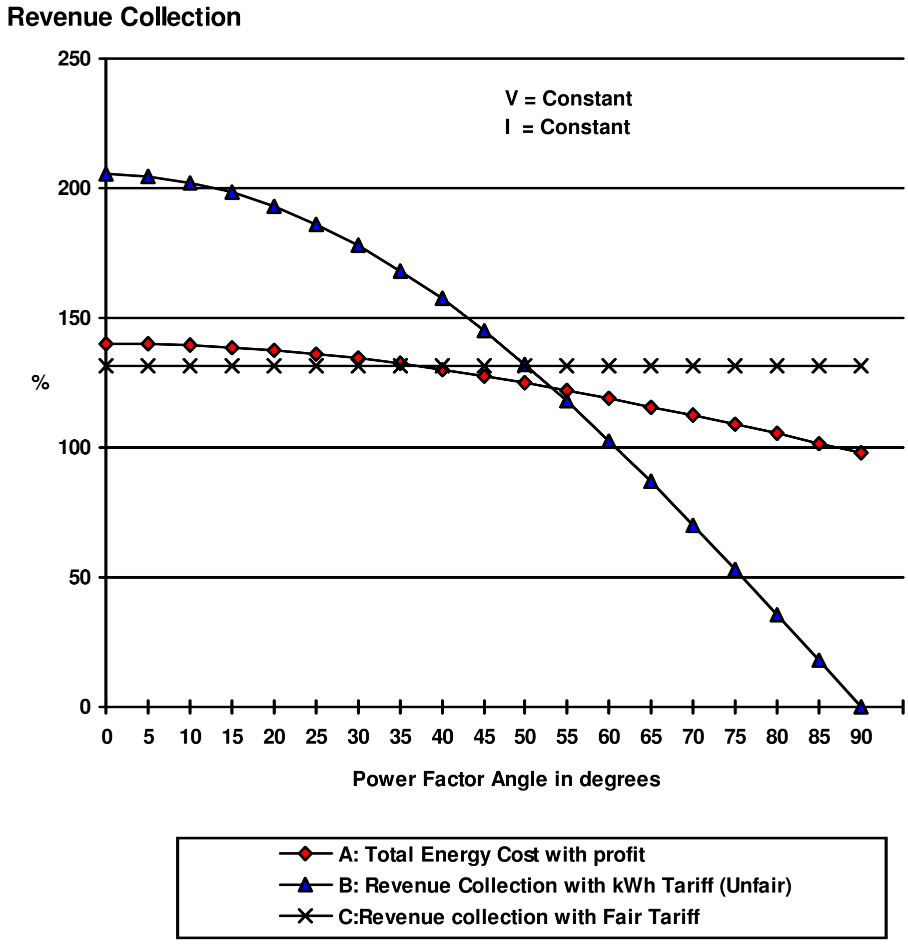

Figure 1. Comparison of revenue collection using two different tariff structures with respect to total energy cost.(plotted with constant kVA load)

4. BASICS OF ELECTRICAL THEORY

The electrical theory given here is compiled from electrical engineering text books [9,10].

4.1 The AC System

A century back, worldwide, the electric supply is chosen to be an alternating current or ac system as the voltage generated by a rotating coil in a stationary magnetic field is an alternating one. According to Faraday's Laws of Electromagnetic Induction with the regular notations,

Voltage or e.m.f, $$e = -\frac{d}{dt}(N\phi) = \omega N\phi_m \sin \omega t = 2\pi f N B_m A \sin \omega t = E_m \sin \omega t \qquad (1)$$

It is clear from the above equation (1), that the voltage or emf is a sinusoidal waveform. As we have indicated earlier [7], it is important for us to respect the term 'sin ωt'. By saying so, we mean that, we, as consumers, should understand that the voltage is alternating, having a sine function of frequency 50 Hz. and use it in the most appropriate and efficient manner using an ideal or resistive load as stated below.

Definition 1. An ideal load for an ac system is one which draws current that has the same waveform that includes shape, frequency, and phase as that of the ac voltage.

Statement 1. A non-inductive resistor fits the definition of an ideal load.

Though the voltage supplied by the utility, normally, contain a small amount of harmonics, due to the irregularities in flux distribution and non-linearity of magnetization curve, these harmonics being small can be ignored without causing significant differences in the calculations.

If we connect a resistive load, then the current waveform would also be a sinusoid similar to the waveform and free from harmonics as shown in Figure 2.

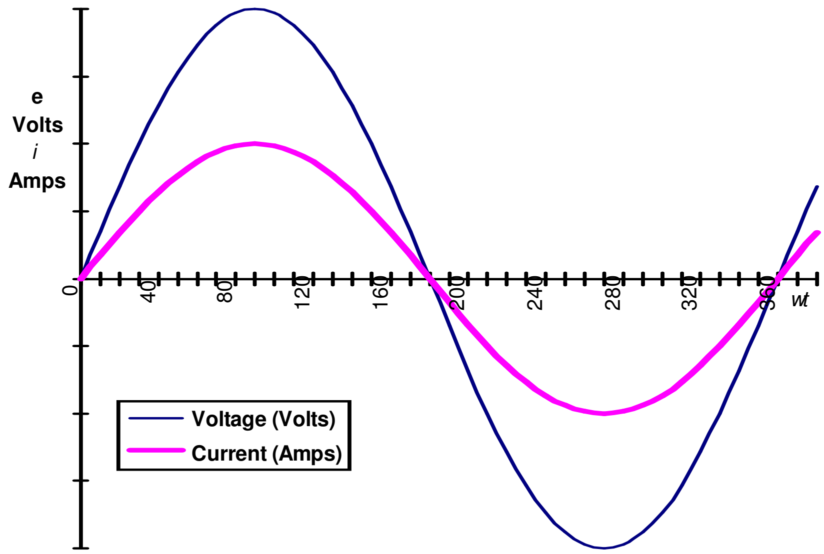

Figure 2. A.C. voltage and current waveforms

4.2 . Taking Heat as the Basis

As we have stressed earlier, the definition of Apparent Energy should have a simple basis. Here we choose 'Heat' as the most natural and simple basis for the definition of Apparent energy.. We first show how active energy is a measure of the heat generated. This leads to the definition of rms value of current using heat as basis [9,10] and later to the definition of Apparent Energy.

4.2.1 Active Energy

For a sinusoidal current, $i = I_m \sin \omega t$, and a pure resistive (ideal) load, R, (as described in Section 4.1 above), the active energy absorbed by a one port network (load) from time t_1 to t_2 , and as given in [9,p.376], is

$$w = \int_{t_1}^{t_2} e(t)i(t)dt = \int_{0}^{t_2} E_m I_m \sin^2 \omega t dt = \frac{E_m I_m}{2}\left(t - \frac{\sin 2\omega t}{2\omega} \right) \quad \text{Joules or Watt-seconds} \quad (2)$$

The active energy absorbed by the one port network or load as given by Equation 2, is converted to heat and dissipated away [10, p.63]. The amount of heat produced is

$$\mathrm{H} = \frac{\text{Energy Absorbed}}{\text{Mechanical equivalent of Heat}} = \frac{\int_{t_1}^{t_2} e(t)i(t)dt}{4{,}186} \quad \text{kilo calories} \qquad (3)$$

Also, the instantaneous power is

$$p = e(t)i(t) = E_m I_m \sin^2 \omega t = \frac{E_m I_m}{2}\left(1 - \cos 2\omega t\right) \qquad \text{Watts,} \qquad (4)$$

The average power, P_{avg}, as derived from Equation 4, is given as,

$$P_{avg} = \frac{E_m I_m}{2} = \frac{E_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}} = E_{rms} I_{rms} = I_{rms}^2 R \qquad \text{Watts} \qquad (5)$$

where E_{rms} and I_{rms} are the rms values of voltage and current respectively. Equation 5 enables us to define the RMS value of a periodic or alternating current using heat as the basis.

4.2.2 Defining RMS value of an Alternating Current using Heat

Definition 2. Effective Value of Current.

The effective value I_{eff} of an alternating (periodic) current $i(t)$ is defined as the steady, d.c., or constant value of current which, when flowing through a given circuit for a given time, will produce the same heat as that produced by the alternating current flowing through the same circuit for the same time period [9, p.313].

The effective current is same as, and also called as, the root mean square (rms) value of current, I_{rms}. It is clear from the above Subsections that the average power which is consumed and dissipated off as heat in an ideal load (heater) is a function of the rms value of voltage and current.

The rms value of current is an extremely important parameter as this dictates the size of the conductors in the various components of the electrical system that carry this current. The cross sectional area of the conductors in the switchgear, cables, transformers is directly proportional to the rms value of current that it carries.

Historically, heat dissipation in the load has been considered a well known measure of the active or useful energy consumed. Active energy could also be used as useful energy in a wide variety of other forms such as to generate light (in lumens) in incandescent bulbs or fluorescent tubes, to generate torque in motors to pump water in irrigation pumpsets, etc. However, for the sake of simplicity and consistency, in this paper, we, too, will consider heat dissipation in the load as a measure of the active energy.

4.3 Need for Defining Apparent Power and Energy

So far, in the above subsections, we have seen and analyzed an ideal case, namely, that of an ideal load. In such a case, we have been able to generate the maximum amount of heat (active energy) in the load, for a certain effective or rms value of current.

However, in case of a non-ideal load, the amount of heat or active energy generated for a certain fixed value of rms or effective current would decrease. Our interest is in knowing the efficiency of the load in generating the heat or active energy for a certain fixed rms value of current.

Apparent energy is an energy parameter whose value does not drop when the load becomes non-ideal or inefficient. Apparent energy can, therefore, be used as a basis and reference for obtaining a measure of the efficiency of the load in generating heat or consuming active energy for a certain rms value of current.

Statement 2. Apparent energy is a measure of the maximum useful (active) energy delivering potential, for a certain effective value (rms value) of current.

4.4 Defining Apparent Power and Energy

Definition 2. The apparent power is defined as

$$VA = E_{rms} I_{rms} \qquad \text{Volt-Amp or VA} \tag{6}$$

Definition 3. The apparent energy is defined as

$$VAh = \int_0^t E_{rms} I_{rms} dt \qquad \text{Volt-Amp-hour or VAh} \tag{7}$$

It is clear from Equations 6 and 7, that we have defined apparent power and energy using the basic voltage and current parameters.

Apparent energy as defined here, is thus, a measure of the maximum heat generating potential in the load for a certain effective or rms value of current.

Apparent power, that is simply the product of two d.c. or constant values- E_{rms} and I_{rms}, is also a d.c. or constant value under steady state conditions. Apparent energy is an integration of the d.c. or constant value, namely apparent power.

Since apparent power establishes a relation between two d.c. or constant values E_{rms} and I_{rms}, rather than a relation between the instantaneous values of the voltage $e(t)$ and current $i(t)$, the apparent power, and, so also the apparent energy, obtained stays at its maximum value uninfluenced by the nature of the load - particularly a non-ideal one.

To stay at its maximum value uninfluenced by the nature of the load, is the much sought after powerful quality of apparent energy that enables it to be used as a basis for computation of power factor which is a measure of the efficiency of the load.

4.5 Power Factor

Definition 4. Power Factor (PF) is the ratio of the active energy to the apparent energy and can be used as a measure of the efficiency of the load in generating heat or active energy for a certain rms value of current.

$$\text{Power Factor} = \frac{\text{Active Energy}}{\text{Apparent Energy}} \tag{8}$$

Statement 3. Power Factor (PF) is also the ratio of the active power to the apparent power.

In the ideal load condition described above, PF is unity. In other words, Active energy or heat generation is maximum for a certain rms value of current, and is equal to its upper limiting value, given by Apparent Energy.

In all other (non-ideal) cases, PF is less than unity. This means that the useful energy consumed by a non-ideal load is less than the maximum amount of useful energy that could have been derived for an effective value of current. The lower the PF, the less efficient the load is in its ability to extract useful energy for an effective value of current.

Earlier, PF in the conventional sense, was used to identify inductive loads and refered to the ratio of the resistive component of the passive load to the total impedance (resistance + inductance / capacitance) of the load. In our case, here, the definition of PF is more broader and encompasses not only inductive loads, but also non-linear and active loads such as the ones that inject harmonics and switching loads. This is elaborated in the following section.

4.6 Effect of Harmonics

Since the r.m.s value of a complex current wave is equal to the square root of the sum of the squares of the r.m.s values of its individual components, considering only odd harmonics, this can be represented as follows.

$$I = \sqrt{I'^2_1 + I'^2_3 + I'^2_5 + \ldots} \qquad (9)$$

Similarly, the r.m.s value of a complex voltage wave can be given as follows.

$$E = \sqrt{E'^2_1 + E'^2_3 + E'^2_5 + \ldots} \qquad (10)$$

The apparent power in the circuit can then be defined as,

$$VA = EI = \sqrt{E^2}\sqrt{I^2} = \sqrt{E^2 I^2} = \sqrt{(E'^2_1 + E'^2_3 + E'^2_5 + \ldots)(I'^2_1 + I'^2_3 + I'^2_5 + \ldots)} \qquad (11)$$

It is clear from the above, that apparent power so computed takes into consideration the RMS value of current. This in turn means that harmonics if injected by the load, would contribute to a higher value of Apparent power and hence apparent energy. Hence, such a consumer would be paying more under the Apparent energy based tariff. Table 1 gives the difference in active and apparent energies when the load injects 3.3 Amps of 3rd Harmonic current along while drawing 10 Amps of fundamental current. We oberve that the active energy meter reading is not affected by the injection of the harmonics, while the apparent energy meter will record more.

Table 1. Active and Apparent quantities for a Load injecting Harmonics

Electrical Parameter	Useful (Active)	Total (Apparent)
Current	10 Amps	10.54 Amps
Power	2400 W	2530 VA
Energy	2.4 kWh	2.53 kVAh

By recording more energy when a load injects harmonics, an apparent energy meter would motivate the consumers to use efficient loads instead, that have filters to block the harmonics from entering the distribution system.

4.7 Wrong Definitions and Measurement Practices for Apparent Energy

The older an engineering discipline, the more resistance it has to change. This is we see even in electricity metering. Particularly in the nineties and initial few years of this decade, we have seen regulatory bodies, utilities and surprisingly even leading meter manufacturers opposing the use of Apparent Energy for PF calculation let alone as a billing and tariff parameter. This is because, traditionally, with electro-mechanical technologies, apparent energy used to be a derived parameter (from active and reactive energies).

Traditionally, the available technologies used to influence the principle of measurement of apparent power or energy. Before the advent of electronic meters, a ‘trivector’ meter would consist of an active energy (kWh) meter, and a reactive energy (kVArh) meter with a special summator between them that is driven through a complicated gearing system to register apparent energy (kVAh). Such an apparent energy meter not only introduces errors due to the approximation techniques adopted, but more importantly because the apparent energy is derived from kWh and kVArh.

It is also important to mention here, that in general, the three phase apparent energy cannot be obtained as a vector sum of the three phase active and reactive energies as is typically measured by the Ferraris meters and many Static meters (see [6]). This is because, firstly, energy is a *scalar* quantity. *The active, reactive and apparent energies are not related to each other*. In case of a three phase system, even the active, reactive and apparent three phase power are not related to each other [6].

The only vector relation that exists is between the single phase active, reactive and apparent power. This also means that the *only power factor that can be correctly defined is the instantaneous power factor* that determines the vector relationship between the single phase power quantities (vectors) - namely active power, reactive power and apparent power. The apparent energy - kVAh cannot be computed as an vector sum of active energy kWh and reactive energy kVArh, nor *by any method from the active and reactive energies* [6].

5. CURRENT APPARENT ENERGY METERING TECHNOLOGIES

Though there has been a number of initiatives by semiconductor manufacturers to support Apparent energy as defined here, the ones that I can recall are given here in chronological order.

In the year 2001, Philips Semiconductors had development a low cost single phase apparent energy (kVAh) metering ASIC that was based on its popular LPC series of microcontrollers that was available for under USD 1. This ASIC however required an analog front end to be built externally.

A few months later, Analog Devices Inc. launched the AD7763, a single phase active cum apparent energy metering chip [11] that is popular even today in the single phase metering segment. This chip incorporates two second order sigma-delta ADCs, a digital integrator, signal processing blocks, reference circuitry and temperature sensors, to perform active and apparent energy measurement. The point to be noted is that before the launch of the AD7763, Analog Devices had launched the AD7753 that included the computation of reactive energy.

The launch of a AD7763 chip at a price lower than the AD7753 indicates two major points –

1. that the reactive energy computation is not required for the computation of Apparent Energy

2. the reactive energy block is an additional block that increases the cost of the chip
3. in the single phase category, too, the focus is changing from reactive energy to apparent energy computation.

In meter development, probably, our centre was one of the first to develop a low cost apparent energy meter in 1996 that records only the single energy parameter. Trials with these meters in Gujarat Electricity Board, GEB's distribution system, had shown the potential of such meters for Tariff based technical loss reduction measures .

Probably Elster (earlier known as ABB) were one of the first amongst meter manufacturers to commercially launch their brand of Alpha meters that had the provision to record and display Apparent energies which is computed as an 'Arithmetic sum' as well as in the old fashioned 'Vector Sum' of Active and reactive energies that mimics the old 'trivector meter'. The Vector sum approach was to suit the CBIP Specifications for A.C. Electrical Energy Meters (Technical report no. 88)[5] that was popular then.

Today, there are numerous single chip metering solutions available from leading semiconductor companies. The meter manufacturers have little choice, but to select one of the low cost solutions. From the above sections, it is clear why the chips and meters that compute apparent energy using the definition described herein are gaining popularity.

5.1 Apparent Energy based Discounted Tariff

For a consumer fitted with an apparent meter, the energy charges with discount/ penalty factor can be given as follows.

ENERGY CHARGES = Discount factor x kVAh READING x OLD kWh TARIFF RATE

In other words, simply multiply the reading of an apparent energy meter by a discount factor ranging from 0.7 to 0.9 and the existing kWh tariff rate to obtain the charges under the proposed new tariff. The power factor is neatly embedded into the apparent energy meter reading making the job of the meter reader and the billing center very easy.

The tariff regulatory authorities can study each consumer category and fix the discount factor accordingly. We propose that the consumer categories where there is already an awareness of power factor clauses, such as the LT industrial and commercial categories could have a discount factor ranging from 0.85 to 0.9. On the other hand, for the LT domestic and LT Agricultural categories, the tariff could be kept optional and with a discount factor ranging from 0.7 to 0.75.

With the trial implementation in Northern India, we are already seeing a change taking place in the mindset of the various consumers. We hope that with a little more effort and less confusion with apparent energy definitions, we will see widespread use of kVAh meters, which would herald an electrical revolution.

Apparent energy metering is a Win-Win solution where the consumers can avail tariff discounts by becoming more efficient while the electric utilities can increase its revenue considerably both through loss reduction and through the collection of penal charges from the defaulting consumers.

There is an interesting side effect that this revolution would have on the labeling of appliances. We will soon a change in the labeling of appliances with its rating indicated in terms of VA and consumption in kVAh. Also, the consumers would check more closely the VA and kVAh figures in their appliances before purchase, instead of the W and kWh figures.

6. CONCLUSIONS

From the above sections, it is clear that energy is a *scalar* quantity. *The active, reactive and apparent energies are not related to each other*. Moreover, apparent energy - kVAh cannot be computed as an vector sum of active energy kWh and reactive energy kVArh.

It is in everyone's interest, and particularly in the interest of technical loss reduction, that we promote a single definition of apparent energy. The definition that is obtained from first principle and given in Section 4.4 should only be considered as the right one.

Thanks to the semiconductor companies, who have promoted low cost metering chips that record apparent energy, the utilities are less averse to the idea of using kVAh as a unit for metering and tariff purposes. The benefits of using kVAh as a tariff unit are numerous and the utilities who have adopted it have already started reaping the benefits of this new tariff.

Our request to the utilities, is however, to offer a larger discount to the consumers in general, and domestic consumers in particular, since their role is vital in the technical loss reduction. Utilities should share a larger portion of the benefits of technical loss reduction to the consumers, as the same is achieved by the active role and participation of the consumers in choosing more efficient appliances from the market often at a higher price. So the consumers should not feel that they are being burdened twice.

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7. Biographies

Vithal Narasinha Kamat (M'1986) was born in Mumbai, on October 22, 1963. He graduated from Birla Vishwakarma Mahavidyalaya, Anand, Gujarat,and completed post-graduation in Control and Instrumentation from the Indian Institute of Technology, Mumbai. He completed his Doctoral studies in Artificial Intelligence from the University of New Brunswick, Canada.

His employment experience includes the Centre for Development of Telematics (CDOT). His fields of interest includes high voltage protection, learning machines, apparent energy tariffs, demand side management, and embedded software

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